

Chapter 2

The Evolution of Seismic Monitoring Systems at the Hawaiian Volcano Observatory

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Abstract

In the century since the Hawaiian Volcano Observatory (HVO) put its first seismographs into operation at the edge of Kīlauea Volcano's summit caldera, seismic monitoring at HVO (now administered by the U.S. Geological Survey [USGS]) has evolved considerably. The HVO seismic network extends across the entire Island of Hawai'i and is complemented by stations installed and operated by monitoring partners in both the USGS and the National Oceanic and Atmospheric Administration. The seismic data stream that is available to HVO for its monitoring of volcanic and seismic activity in Hawai'i, therefore, is built from hundreds of data channels from a diverse collection of instruments that can accurately record the ground motions of earthquakes ranging in magnitude from <1 to ≥ 8 . In this chapter we describe the growth of HVO's seismic monitoring systems throughout its first hundred years of operation. Although other references provide specific details of the changes in instrumentation and data handling over time, we recount here, in more general terms, the evolution of HVO's seismic network. We focus not only on equipment but also on interpretative products and results that were enabled by the new instrumentation and by improvements in HVO's seismic monitoring, analytical, and interpretative capabilities implemented during the past century. As HVO enters its next hundred years of seismological studies, it is well situated to further improve upon insights into seismic and volcanic processes by using contemporary seismological tools.

Introduction

The U.S. Geological Survey (USGS) Hawaiian Volcano Observatory (HVO) has been conducting routine volcano monitoring and continuous measurement programs from the rim of Kīlauea Volcano's summit caldera since 1912. HVO put its first seismographs into operation on July 31, 1912, which began more than 100 years of seismic monitoring at Kīlauea and on

the Island of Hawai'i. Over the past century, thousands of scientific reports and articles have been published in connection with Hawaiian volcanism, and an extensive bibliography has accumulated, including numerous discussions of the history of HVO and its seismic monitoring operations, as well as research results. From among these references, we point to Klein and Koyanagi (1980), Apple (1987), Eaton (1996), and Klein and Wright (2000) for details of the early growth of HVO's seismic network. In particular, the work of Klein and Wright stands out because their compilation uses newspaper accounts and other reports of the effects of historical earthquakes to extend Hawai'i's detailed seismic history to nearly a century before instrumental monitoring began at HVO. Doing so required that they account for seismic monitoring capabilities throughout HVO's history in order to better evaluate historical accounts when instrumental records were unavailable or limited.

We present here an updated discussion of the seismic monitoring systems at HVO. Rather than casting our discussion to include extensive details of instrumentation, our aim is to speak to the evolution of HVO's seismic network and monitoring practices in terms of the capabilities and data collection thus afforded by changes to the network. Readers who seek greater detail regarding instrumentation can consult the publications mentioned above, as well as the series of HVO weekly, monthly, and even annual reports and summaries (see compilations by Fiske and others, 1987, and Bevens and others, 1988).

Early Instrumental Monitoring, 1912–50

To begin systematic seismic monitoring of Kīlauea Volcano in 1912, HVO founder Thomas A. Jaggar, Jr., purchased two instruments from Fusakichi Omori of the University of Tokyo and installed them in HVO's Whitney Vault (see Tilling and others, this volume, chap. 1). Omori had pioneered seismological research in Japan, including the study of seismicity of both volcanic and nonvolcanic origins, and Jaggar's interest was to establish similar observing and monitoring capabilities at Kīlauea. One of the Omori instruments installed in 1912 was an

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“ordinary” seismograph, meant to record relatively strong local earthquakes; the other was referred to as a “heavy” seismograph that, because of its mass, was capable of registering relatively weak ground motions, such as those produced by teleseisms.

To set up the seismographs at HVO, Jagggar enlisted Harry Wood, who was working at the University of California, Berkeley, at the time. Wood arrived in Hawai‘i in summer 1912 and, in addition to installing and maintaining the seismographs, documented the seismic activity recorded by them. Wood left HVO in 1917 and, after World War I, was commissioned to establish a seismic network in Southern California in cooperation with the California Institute of Technology (Caltech). Among Wood’s contributions at Caltech was his construction, with astronomer John Anderson, of the Wood-Anderson torsion seismometer (Anderson and Wood, 1925). Regional deployment of these seismometers led to Charles Richter’s publication of his magnitude scale for local earthquakes (Richter, 1935).

At Kīlauea, the heavy Omori seismograph routinely and clearly registered microseismic background noise that, in Hawai‘i, is closely linked to oceanic swells. In addition, the instrument recorded signals that generally correlated with visible lava activity at Kīlauea’s summit and that were subsequently called “volcanic vibrations” (Wood, 1913). The November 25, 1914, eruption of Mauna Loa was preceded by about 2 months of seismicity recorded on the two HVO seismographs. Although instrumentally determined epicenters were not available from the single station that was in operation at that time, estimated distances of the recorded earthquakes suggested their origin to be beneath Mauna Loa (Wood, 1915).

Like other contemporary instruments, the Omori seismographs were large mechanical devices whose sensitivity to (or magnification of) ground movement resulted from their overall size (Wood, 1913). The two Omori instruments first brought to Hawai‘i did not feature viscous damping. To more accurately

record ground motion, the J.A. Bosch firm of Strasburg modified the original Omori design to add damping, and Jagggar subsequently complemented his two Omori instruments with Bosch-Omori seismographs (fig. 1). HVO continued to operate these Bosch-Omori instruments until 1963 (Apple, 1987).

Seismology in the early 20th century was at an early evolutionary stage, with much effort dedicated to collecting more and better data by improving the designs of seismometers, timing mechanisms, and recording instruments. To promote its volcano and seismic monitoring, HVO also undertook its own seismograph design and fabrication efforts to achieve greater instrument sensitivity and ease of installation and operation. The resulting instruments were deployed in Hawai‘i and later installed at stations in Alaska and California.

HVO installed additional seismographs as they became available, at Hilo in 1919, Kona in 1922, and Hīlea in 1923. The distribution of seismic stations in 1923, reflecting the need to locate instruments at relatively accessible locations where hosts agreed to serve as observers and record changers, is mapped in figure 2A. Along with the instruments installed on Kīlauea at HVO, these additional stations expanded volcano and earthquake monitoring coverage on the island. HVO staff compiled lists of event times, including tremor, local earthquakes, and teleseisms, which were reported in HVO’s weekly and monthly bulletins (Bevens and others, 1988; Fiske and others, 1987). Sizes of local earthquakes, as determined from amplitudes measured on available instrumental records, were also provided (Klein and Wright, 2000).

A principal—possibly the most basic—goal of seismic monitoring was, and continues to be, the accurate cataloging and reporting of earthquake time, location, and size. Time reference at the early HVO seismographic stations was provided by means of Howard precision astronomical clocks that were wired to produce reference marks on the records by lifting the recording pens once per minute. Earthquake epicenters were determined graphically on the basis of estimates of the respective distances between recording stations and earthquakes, as derived from seismic-wave traveltimes. Wood (1914) initially selected travelttime-versus-distance curves, compiled by Conrad Zeissig for earthquakes and seismic stations in Europe, to provide these estimates for Hawai‘i.

Ruy Finch, who assumed seismological tasks at HVO in 1919, resumed estimating the distances between earthquakes and seismographic stations, which had been abandoned since Wood’s departure from HVO in 1917. Finch also changed this procedure by using the time-distance tables, compiled and published by Omori, which were tabulated over shorter distance ranges and considered to be more suited for application in Hawai‘i, to determine earthquake locations (Finch, 1925).

After working for several years to establish seismographic stations and volcano observatories on Mount Lassen in California and in the Aleutian Islands, Austin Jones came to HVO in 1931 to study the relationships between local earthquakes and episodes of ground tilt at Kīlauea. As described by Jones (1935), sufficient data had been compiled to produce travelttime tables from the data compiled for earthquakes in Hawai‘i, and

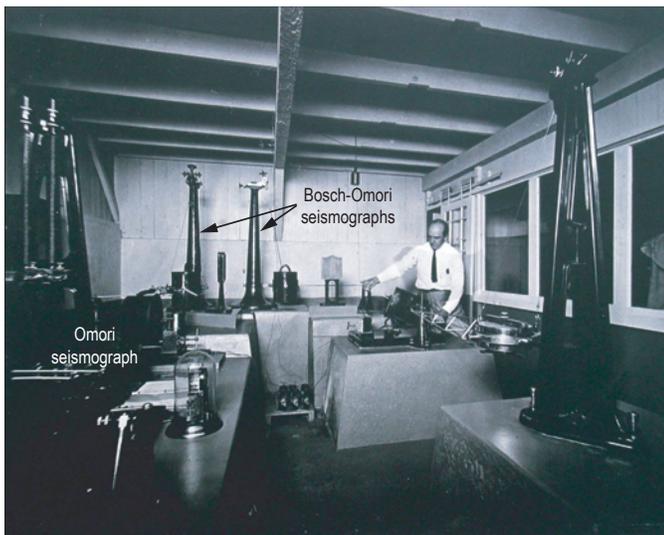


Figure 1. Thomas A. Jagggar, Jr., founder of the Hawaiian Volcano Observatory, in the Whitney Vault, with Omori and Bosch-Omori seismographs at left edge and back, respectively.

to more routinely determine and publish earthquake locations from the data recorded at HVO's seismographic stations. The HVO seismic network configuration in 1934, with three stations located in the Kīlauea summit caldera region, one in Hilo, and another in Kona, is mapped in figure 2B. The Hīlea station was discontinued in 1927 (Jones, 1935), but another station had been added at Waiki'i, on the west flank of Mauna Kea, and the seismic network began to approach an islandwide monitoring footprint. Jones also initiated a more quantitative means of determining earthquake size from the amplitudes of ground motion on seismograms (Klein and Wright, 2000), although he

did not account for the distances between recording stations and earthquake locations, as is required for determining earthquake magnitudes on the basis of amplitude.

Throughout the 1940s, HVO's volcano and seismic monitoring capabilities remained stable while being somewhat bolstered by attention to instrument design and fabrication. Significant to the monitoring was the addition in 1938 of seismic station MLO on Mauna Loa's southeast flank, as shown in figure 2C. Tabulation of earthquakes and seismic activity continued all the while, evolving to the point where graphically estimated earthquake locations, including focal depths, were routinely

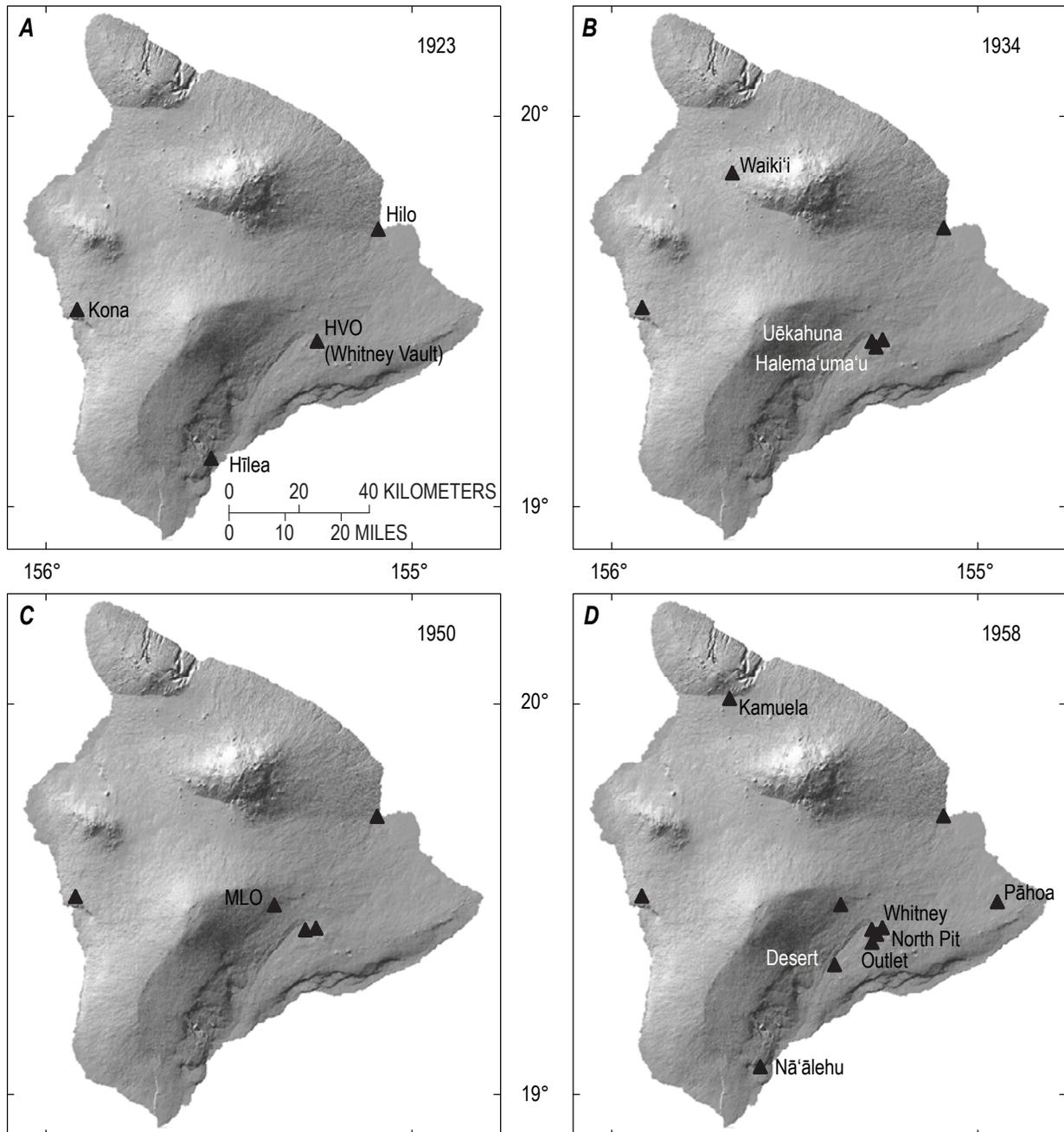


Figure 2. Island of Hawai'i, showing locations of seismographic stations (triangles) operating in 1923 (A), 1934 (B), 1950 (C), and 1958 (D).

being reported. The compilation by Klein and Wright (2000) speaks clearly to the quality and commitment of the effort that was made in data collection and record keeping. The Hawaiian earthquake catalog built by Klein and Wright (2000) included more than 16,000 earthquakes, from the time when HVO's first seismometer was put into operation in 1912 through 1953.

More Sensitive Instruments, Data Telemetry, Earthquake Magnitudes, and Increased Recording Capacity, 1950–70

In the 1940s, HVO staff recognized that seismic monitoring required upgraded capabilities and increased network sensitivity, which would improve HVO's ability to detect, reliably locate, and catalog seismicity of interest in Hawai'i. The plan was to first deploy more seismographs, and in 1950 the first Loucks-Omori instrument, built by HVO machinists Burton Loucks and John Forbes, was installed at the Hilo station (Pleimann, 1952; Eaton, 1996). As suggested by its name, the Loucks-Omori seismograph was a modification of the original Omori design. Though still a mechanical system, the nominal magnification of ground motion afforded by the Loucks-Omori instruments was times-200, somewhat greater than that of the Bosch-Omori and other HVO instruments in operation at the time.

Hired to take part in HVO's seismic network expansion and modernization, Jerry Eaton arrived at HVO in fall 1953. His Ph.D. dissertation, "The theory of the electromagnetic seismograph" (subsequently published in brief form as Eaton, 1957), established him as an authority in the field. Bringing this background to HVO, Eaton transformed seismic monitoring by creating the means to expand the HVO seismic network to include more stations and, by tuning the instrumentation, to be able to record the many small earthquakes related to active volcanism in Hawai'i (Eaton, 1996).

Eaton experimented by recording earthquakes on instruments built to have different frequency-response characteristics. His observations allowed him to specify the design of an electromagnetic seismograph, eventually referred to as the HVO-1, that was better suited to record small earthquakes in Hawai'i than the Bosch-Omori or the Loucks-Omori seismographs. The instrument that resulted from this effort was significantly more sensitive; its peak magnification was ~25,000 at a period of 0.2 s. Seismographs of this design eventually replaced older instruments at the Uēkahuna, Hilo, Pāhoa, Kamuela, and Nā'ālehu stations.

Eaton also advanced the real-time seismic monitoring of volcanic activity (Eaton, 1996). He simply wanted a means to record visibly, as opposed to photographically, small earthquakes related to eruptions. Eaton experimented with different combinations of available seismometers, preamplifiers, and pen recorders until he identified a combination that offered the desired sensitivity. During testing of the system, the HVO

building (where the recorder was on display) was found to be too noisy for the sensitive seismometer. The seismometer and preamplifier were eventually moved to the Outlet Vault, some 3 km away from HVO, and the signals were transmitted over that distance via cable to the recorder at HVO. This was the prototype of a telemetered seismograph, called the HVO-2.

Eaton's HVO-2 seismometers were more sensitive than the HVO-1, with a peak magnification of 40,000 at 0.2 s, and they also afforded, by way of telemetry between HVO and the seismic stations, the ability to extend monitoring coverage over greater distances. Because the available data-transmission scheme consisted simply of telephone cables between the seismometers and recorders, deployment was restricted to areas where it was feasible to establish cabled connections. By 1958 literally miles of cables extended from HVO to the stations at Mauna Loa, Desert, Outlet, and North Pit, all of which were equipped with HVO-2 seismometers. With additional installations of Loucks-Omori instruments, an expanded and improved HVO seismic network was beginning to take shape (fig. 2D).

Throughout this period of network growth, earthquake data processing continued much the same way it had previously. Analysts read and compiled seismic-wave-arrival times from paper records. Earthquake locations were determined graphically, fitting the measured traveltimes to those postulated from earthquakes at provisional or hypothetical locations among the recording stations. Such techniques as implemented at HVO were described by both Jones (1935) and Macdonald and Eaton (1964).

In addition to the sensitive seismographs that he designed, Eaton also installed standard Wood-Anderson seismographs (Anderson and Wood, 1925), initially at his residence in Hawai'i Volcanoes National Park and subsequently at Haleakalā (Maui) in late 1956 and at Hilo in 1958. With these instruments, Eaton was also able to quantify earthquake magnitudes systematically according to the Richter scale, as used with the Wood-Anderson seismographs deployed in Southern California (Richter, 1935). Although the practice and procedures of determining earthquake magnitudes have since evolved and become computerized and automated, Eaton's work can be viewed as the beginning of HVO's production of modern seismicity catalogs, containing earthquake hypocenters, origin times, and magnitudes.

The evolution of HVO's high-gain seismographic network resulted in orders-of-magnitude increases in the numbers of earthquakes recorded, precisely timed, and located (Eaton, 1996). Consistent and careful processing of larger numbers of earthquakes was necessary to identify temporal behaviors and source regions, as well as to infer or associate these data with source processes within the magmatic systems and volcanic edifices.

Using seismic-wave traveltimes to infer simple, depth-varying seismic-wavespeed distributions and earthquake locations derived from the expanded and improved HVO seismic network, Eaton was able to articulate a general structural model for an idealized Hawaiian volcano. Combining these insights with those obtained from deformation (the measurement of which was also improved by Eaton; see

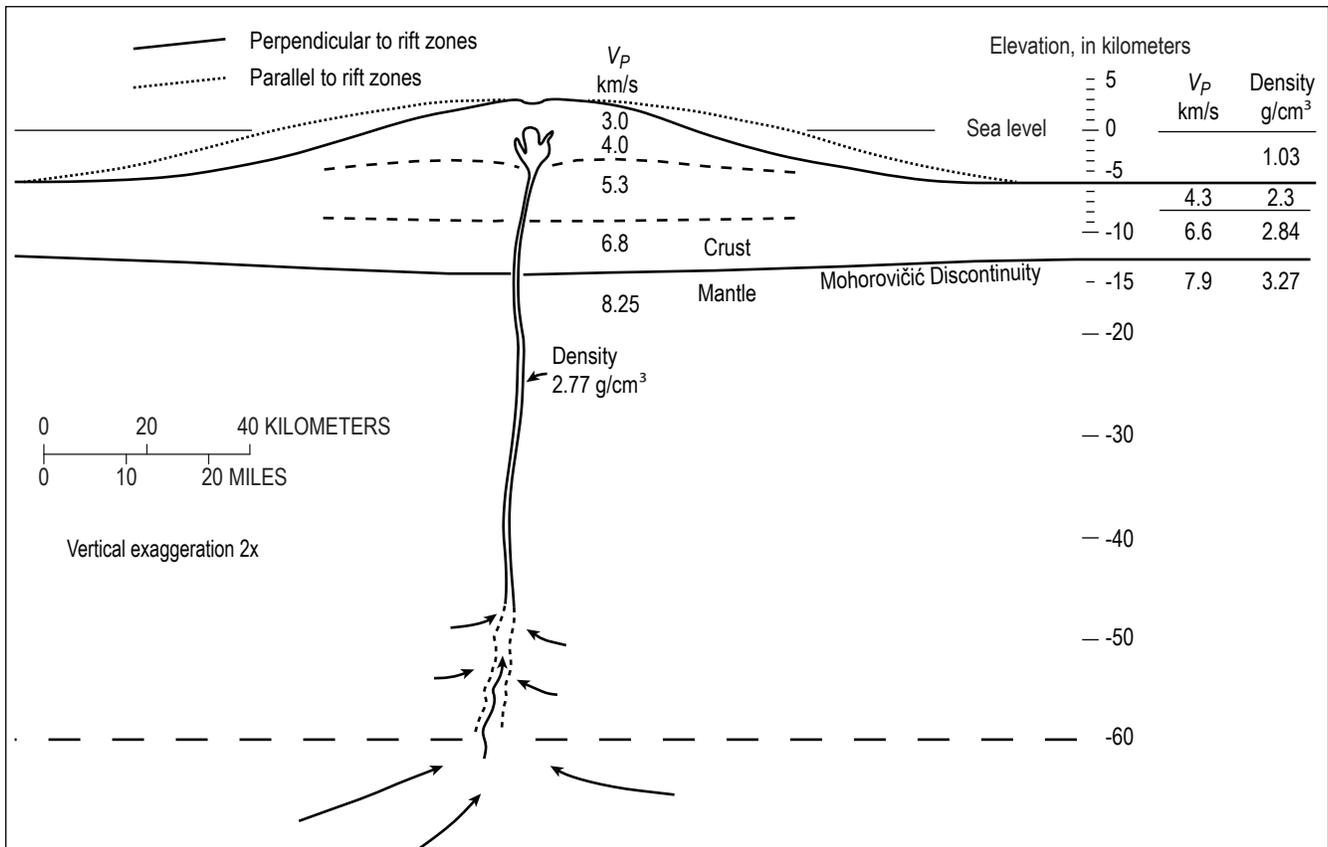


Figure 3. Idealized model of an active Hawaiian volcano, originally published by Eaton and Murata (1960), as inferred from local earthquake traveltimes and locations and corroborated by deformation, geologic, and geochemical data.

Poland and others, this volume, chap. 5), geologic studies, and geochemical monitoring, Eaton and HVO colleague K.J. Murata constructed the first model for the structure and growth of a Hawaiian volcano (fig. 3) in their seminal research paper titled “How Volcanoes Grow” (Eaton and Murata, 1960). Eaton further used the improved seismic data to argue for a slight deepening of the crust/upper mantle boundary, or Mohorovičić Discontinuity, directly beneath the island. He also suggested that the locations of volcanic tremor and swarms of deep earthquakes, 60 km directly beneath Kīlauea Caldera, highlighted a mantle source feeding the volcano and that the ground-surface deformation and earthquake patterns noted during eruptions or accompanying inferred magma movement suggested a shallow magma reservoir several kilometers beneath Kīlauea’s summit caldera (Eaton, 1962).

The growth of HVO’s seismic network over time, beginning with its push toward modernization in 1950, is plotted in figure 4, along with numbers of station sites, recorded ground-motion components, and processed earthquakes, as well as indications of HVO’s principal seismic data-recording platforms. We begin the curve with data points representing earthquakes processed in 1959, marking the earliest date for which reading sheets with phase-arrival time entries for local earthquakes have been recovered at HVO and their arrival-time readings transferred to computer files.

Although the footprint of HVO’s seismic network evolved over the years, earthquake hypocentral solutions dating back to 1959 were recomputed to ensure catalog consistency over time, across significant changes to HVO’s routine earthquake location and magnitude determination procedures. The curve ends in 2009, when HVO made significant improvements to both its field seismographic stations and its seismic computing environment. Data since 2009 are yet to be finalized (as of September 2014) with the upgraded capabilities afforded by these changes.

Abrupt changes appear in the curves in figure 4 as changes affording increased data flow or new stations were introduced. Overlap among the different recording/analysis platforms, indicated across the bottom of this figure, should be understood to reflect HVO’s commitment to preserving continuity and consistency of the record where appropriate. For the earlier times shown in figure 4, data were written exclusively to drums with either smoked or photosensitive papers. Throughout the entire interval shown in figure 4, HVO continued to record signals from key stations on drum papers. The drum recorders showed as much as a full day’s continuous and real-time seismic record, affording rapid visual recognition and assessment of seismic activity. Over time, though still providing critical value to HVO’s monitoring and interpretative capabilities, the paper records

gave way to other recording platforms, including the Develocorders and the Eclipse and CUSP systems (see below), for HVO’s routine seismic data processing and earthquake cataloging.

Overall, the number of components grew steadily with the number of station sites. A notable exception to this trend occurred between 1958 and 1960, when the number of recorded components plotted in figure 4 appears to jump because new stations featured multiple components, including horizontal as well as vertical sensors. As described above, some of the stations were equipped with Wood-Anderson horizontal seismographs that provided HVO with the capability of determining earthquake magnitudes according to Richter’s formulation for Southern California (Richter, 1935).

In 1961, Eaton moved to Denver, Colo., to join the USGS Crustal Studies Branch and conduct crustal refraction and earthquake studies in the western United States. He left HVO with its modern seismic instruments telemetering data in a truly networked operation. Just as important, he provided a template for HVO’s seismic network expansion. The years after Eaton’s departure from HVO were a period of steady seismic network growth and improvement. Seismographic stations were added, both as “outstations” that recorded locally at the remote sites and as “networked” stations that were connected to recorders at HVO by way of upgraded cables laid within and near Kīlauea’s summit. By 1967, as plotted in figure 4, HVO was collecting several dozen smoked-paper and photographic seismograms daily from its seismic network.

Microearthquake Monitoring Developments at HVO and in California

In 1965 Eaton moved from Denver to Menlo Park, Calif., to join and help build the USGS’s earthquake research program, the creation of which was spurred by the great Alaska earthquake of 1964; the group in Menlo Park was particularly focused on the San Andreas Fault System. Two related aspects of this program were determination of crustal structure and mapping of the details of active fault structures, using relatively dense networks of sensitive seismometers to record microearthquakes. Eaton’s experience with instrument development and network deployment at HVO demonstrated the importance of matching overall network system response to the earthquakes of interest and the region of study. This approach was embraced as an important design principle for the microearthquake monitoring efforts undertaken in California (Eaton, 1977, 1992).

Eaton and others (1970) demonstrated the value of microearthquake recording with closely spaced, high-gain, short-period instruments in their study of aftershocks of the June 27, 1966, Parkfield earthquake that ruptured the San Andreas Fault in central California. With sensitive seismometers deployed in close proximity to the fault (and, therefore, the earthquakes of interest), Eaton and coworkers were able to locate hundreds of aftershocks in this sequence. Hypocentral precision was sufficient to map fault complexity at depth that could be associated with surface observations. Although a planar rupture surface is a reasonable approximation for a faulting event, the distribution of hypocenters in the aftershock sequence of the 1966 earthquake suggested a

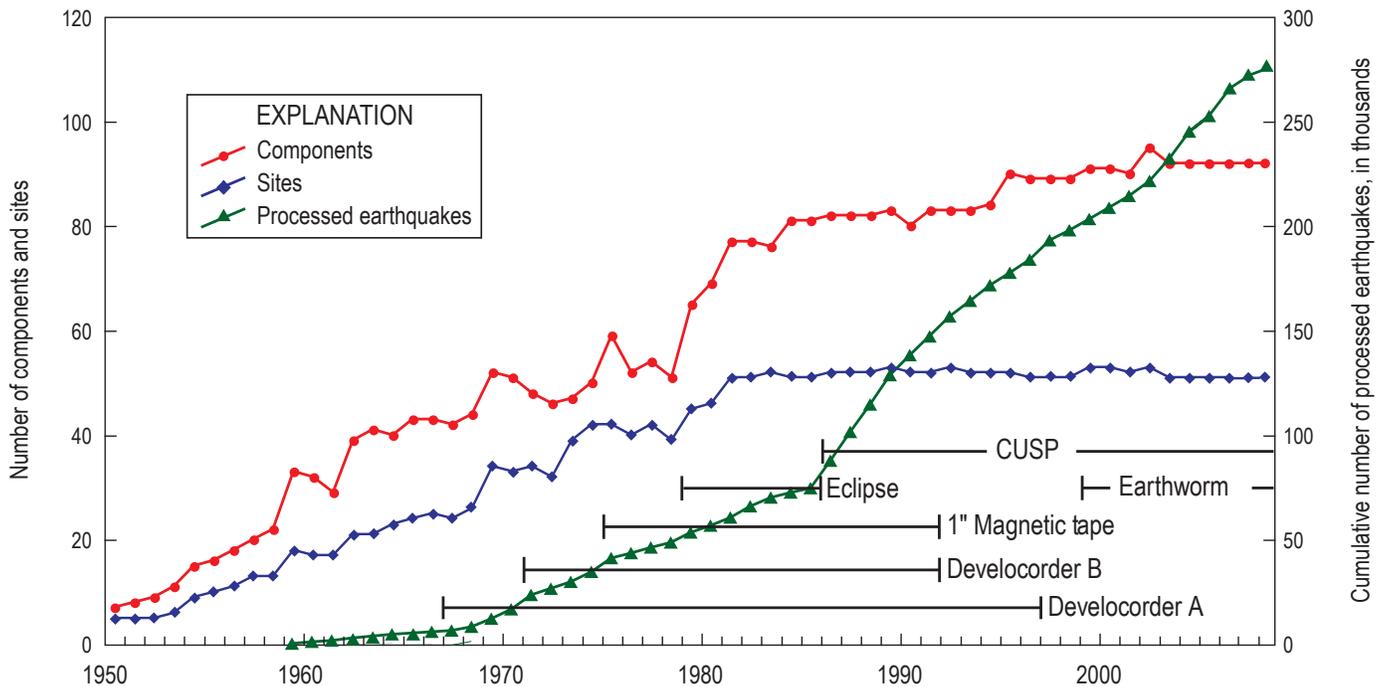


Figure 4. Evolution of the Hawaiian Volcano Observatory (HVO) seismic network from 1950 through 2009, in terms of numbers of station sites (diamonds), recorded ground-motion components (dots), and processed earthquakes (triangles). Plotted across bottom are HVO intervals of seismic acquisition and processing systems, with their operational times reflected by lengths of horizontal lines.

more complex fault structure in which associated patterns of measured fault displacements and tectonic-strain-energy release varied, both along fault strike and with depth. The data also suggested that the geometric complexity of the San Andreas Fault, as indicated by the clustering of aftershock hypocenters, affected the dynamic rupture associated with the main shock (Eaton and others, 1970).

As USGS microearthquake monitoring efforts in California progressed, valuable products and insights became available to the seismic monitoring community. Eaton and colleagues in Menlo Park published numerous reports related to USGS's California seismographic network, essentially defining and shaping microearthquake-monitoring practice in the United States (see summary discussions by Lee and Stewart, 1981). The Menlo Park USGS group, led by Eaton, shared seismic network resources with HVO, allowing HVO to keep pace with evolving seismic monitoring technologies.

One of the key pieces in the early Menlo Park microearthquake monitoring program was the Develocorder, a 20-channel photographic recorder that continuously captured seismic-trace inputs onto 16-mm reels of microfilm. The

Develocorder automatically fixed and stored the microfilm so that a record showing the 20 channels of data was available for viewing within 11 minutes of receiving the data inputs. In 1967, a Develocorder was delivered to HVO (fig. 5). By the end of the year, it was in operation and became a mainstay of HVO's seismic monitoring effort until 1997.

The Develocorder afforded HVO a way to quickly and visually determine where an earthquake had occurred. A Develocorder display of earthquakes recorded during a swarm in Kīlauea's upper East Rift Zone in 1992 is shown in figure 6. The data traces from top to bottom of the film were assigned and grouped according to station location. By viewing the times of seismic-wave arrivals at different stations, relative to one another, the proximity of the earthquake to the stations on display could be visually determined. Depending on whether and how the patterns of arrivals changed, possible migration of hypocenters or other changes in seismic activity could also be visually assessed.

Though proceeding somewhat deliberately, HVO's seismic network growth and the high rates of seismicity recorded by the network produced volumes of individual paper-drum records that were awkward, if not difficult, to read, interpret, and store. The introduction of the Develocorder and a companion offline viewer with a magnifying screen provided a means to efficiently scan the record for events and other seismic activity of interest. The viewer's magnification also afforded greater timing precision for measuring seismic-wave arrivals. Arrival times read from seismograph drum-paper records were typically read to the nearest 0.1 s, whereas the Develocorders were read to the nearest 0.05 s. With the practice of recording two time references, along with 18 seismic data traces on both Develocorder films, the traces from different stations all shared a common reference time base.

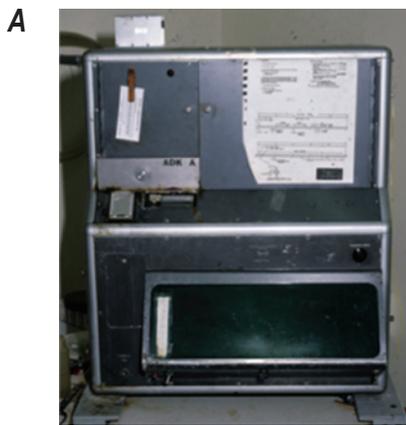


Figure 5. Develocorder seismic-recording equipment used at the Hawaiian Volcano Observatory (HVO) from 1967 to 1997. *A*, Recording unit, with photographic system containing film reels and film-developing stage at top and lit screen for viewing film shortly after being developed and fixed at bottom. *B*, Offline viewer for Develocorder films, with HVO analyst measuring seismic-wave-arrival times.

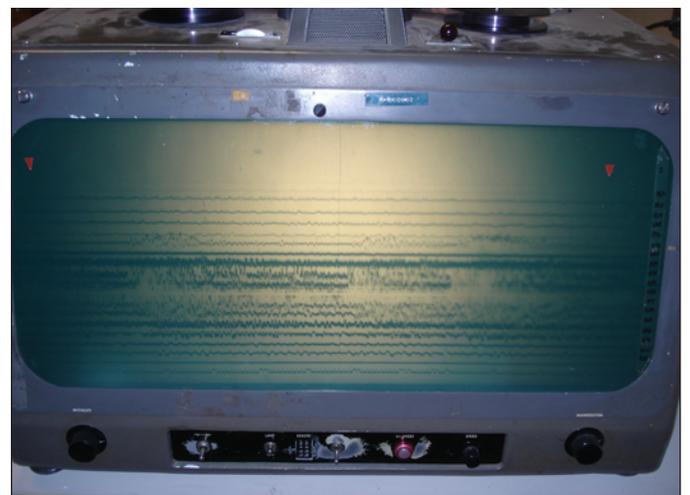


Figure 6. Closeup of Develocorder viewer, showing earthquakes recorded during a dike intrusion into Kīlauea's East Rift Zone in 1992. Data traces on Develocorders at the Hawaiian Volcano Observatory are arranged by region to allow qualitative visual assessment of earthquake locations by looking at arrival patterns among displayed data channels.

The interval throughout the 1960s and mid-1970s shows steady increases in the number of station sites and in the number of components or channels of data recorded (fig. 4). Beginning in the mid-1960s, gradual replacement of cables along the ground in favor of radio telemetry made it somewhat easier to establish data links. Radio telemetry also facilitated expansion of the network into new and remote areas. A second Develocorder, operational in 1971, provided recording capacity for 18 more seismic data channels.

Computer Processing of Earthquake Locations, 1970–85

By 1970, the HVO seismic network had expanded into Kīlauea's rift zones (fig. 7). The increase in the number of stations there improved upon the ability to discriminate between shallow rift-zone seismicity and deeper earthquakes beneath Kīlauea's south flank. To more appropriately and efficiently work with the expanded and improved microearthquake datasets, HVO abandoned its graphical procedures for manually locating earthquakes in 1970 in favor of computer-based earthquake location procedures (for example, Endo and others, 1970).

Computer processing of HVO seismic data was a joint project between HVO and the USGS National Center for Earthquake Research in Menlo Park, Calif. Eaton had written the computer program HYPOLAYR (Eaton, 1969) to locate local earthquakes

in California. This program featured the calculation of P-wave traveltimes between trial hypocenters and recording stations from a specified seismic-velocity model composed of flat-lying, homogeneous crustal layers, instead of interpolating between entries of precompiled traveltime tables, as in other programs. HYPOLAYR ran in batch mode, locating earthquakes from P-wave arrival-time readings, and computed earthquake hypocenters and magnitudes, along with formal errors.

The work involved with the computer locations was divided between Menlo Park and HVO. Analysts at HVO scanned Develocorder films and paper records for earthquakes, identified first-arrival picks, and measured the arrival times on Develocorder films and paper records. Reading sheets were sent to California, and the arrival times were punched onto computer cards. The readings were input to HYPOLAYR, which ran on the USGS computer in Menlo Park. Both input card decks and output decks created by HYPOLAYR were saved for possible further analysis.

The basic product of these efforts was an analyst-reviewed catalog of Hawaiian seismicity. The start of routine computer-based earthquake data analysis is recognized in figure 4 as the increase in the number of earthquakes processed after 1970. The greater numbers of located or processed earthquakes bolstered and added dimensions to interpretative discussions of volcanic and seismic processes in Hawai'i. HVO seismicity catalogs were initially published quarterly (see Nakata, 2007). After the implementation of computer-based hypocentral estimation at HVO, as described below, the catalogs were produced as annual summaries of seismicity (for example, Nakata and Okubo, 2009).

Koyanagi and Endo (1971) presented the first computer-based HVO compilations for seismic activity recorded in 1969. Beginning in 1966, HVO had begun to distinguish earthquake types beneath Kīlauea's summit region on the basis of the appearance and frequency content of their radiated waveforms, and the "long period," or LP, designation for Kīlauea summit earthquakes was added to the HVO seismicity catalogs (fig. 8). They noted temporal associations of earthquake swarms and of different types of earthquakes with eruptive episodes in Kīlauea's East Rift Zone at Mauna Ulu. Clustering of earthquakes, evident in their cross section and indicating different event types through different phases of eruption, added detail to the general model proposed by Eaton and Murata (1960). The earthquake locations and classifications subsequently factored into an early model of the relation between seismicity, dike intrusion, and seaward movement of Kīlauea's south flank (Koyanagi and others, 1972) and discussion of the processes related to the 1969 Kīlauea East Rift Zone eruption (Swanson and others, 1976). Koyanagi and others (1976) added interpretative details beneath Kīlauea's summit caldera to the sketch suggested by Koyanagi and Endo (1971). Koyanagi and others (1976) focused on swarms of earthquakes of different types near Kīlauea Caldera to describe the magma conduits and reservoirs in that area.

Ryan and others (1981) constructed a physical model to display seismicity throughout Kīlauea as a step toward a model

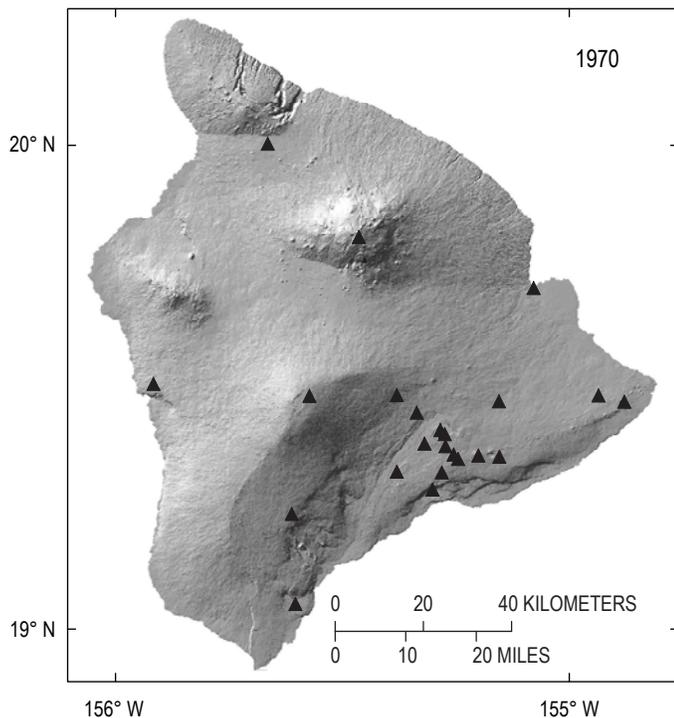


Figure 7. Island of Hawai'i, showing location of seismographic stations operating in 1970.

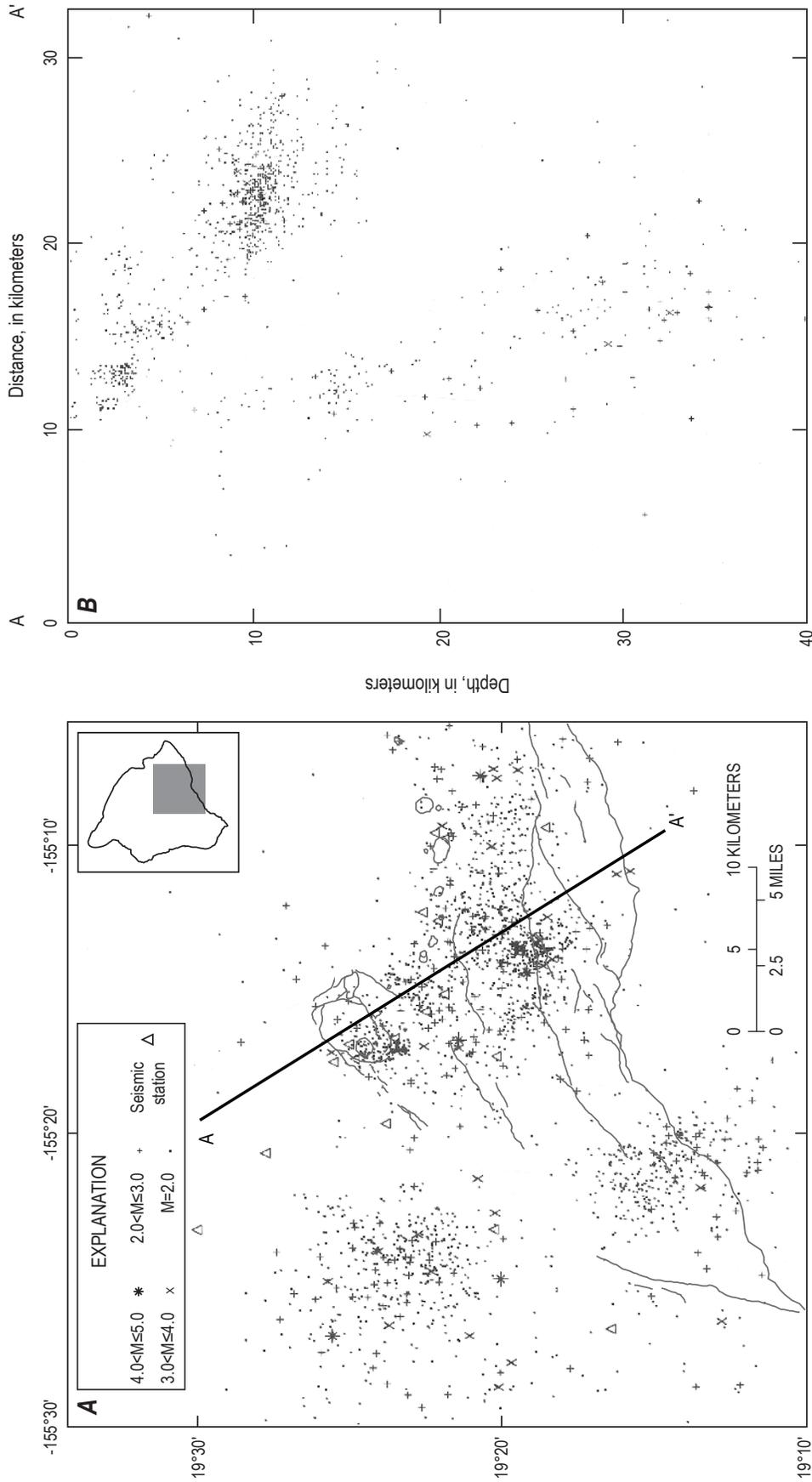


Figure 8. Seismic activity in southeastern part of the Island of Hawaii in 1969, as originally presented by Koyanagi and Endo (1971). A, Kilauea and southeast flank of Mauna Loa, showing locations of earthquake epicenters, with symbols indicating earthquake magnitude. B, Cross section projected onto plane parallel to line A-A' in part A, showing locations of earthquakes lying within 4 km of line A-A'.

of Kīlauea's magma-transport system. Using event classifications as well as hypocentral distributions, they identified both a primary conduit feeding magma into Kīlauea from the upper mantle and conduits feeding magma into Kīlauea's upper East Rift Zone; they also articulated features within Kīlauea's summit caldera complex. Their resulting model offered a multidisciplinary interpretative framework that built upon earlier work, such as that of Eaton and Murata (1960).

Though not immediately included in HVO routine data processing, a Bell & Howell 3700 FM analog tape recorder was brought to HVO in summer 1975 and used to record the full complement of telemetered HVO seismic data onto analog tapes. HVO did not immediately acquire an accompanying tape-playback utility, but HVO analysts compiled lists of events of interest and sent those, along with the FM tapes, to Menlo Park for dubbing or copying selected events onto another FM tape. With 14 recording tracks, each capable of storing the equivalent of eight seismic channels, the full capacity of the Bell & Howell recorder was 112 data channels. This extra capacity was used to add more stations and to augment stations with horizontal seismometers in order to improve the recognition of seismic S-waves that provide added constraint on computed earthquake hypocenters. After 1980, relatively few new station sites were added to HVO's seismic network, although the addition of horizontal seismometers at existing sites continued.

In 1979 computer-based earthquake data processing at HVO began when HVO acquired a Data General Eclipse computer and equipment to set up FM tape playback and digitizing capabilities. With its new platforms to acquire and manipulate seismic data, HVO modified its seismic processing routine accordingly. Data analysts continued to scan Develocorder films to assemble hourly and daily earthquake counts. Instead of measuring the arrival times of larger events on the Develocorder viewer, however, they compiled lists of events longer than 40 s—the equivalent of a $M1.5$ earthquake. Analysts used the lists for transferring data from the FM tapes to the computer, where waveform data, nominally sampled at 100 Hz, from the entire telemetered network were reviewed. Events were picked using a graphics computer terminal that registered arrival-time or pick information onto the Eclipse computer. Parametric and waveform data were subsequently archived to nine-track computer tapes. The timing precision of arrival times measured on the graphics terminal improved to 0.01s for all of the telemetered data channels.

An important piece of HVO's Eclipse computing configuration was the HYPOINVERSE earthquake location program, written by Fred Klein (Klein, 1978). Central to HYPOINVERSE and to earthquake location programs in general is the method used to solve the problem of forward-calculating seismic wave traveltimes through a specified model of seismic wavespeeds. The misfit between observed and calculated traveltimes based on the locations of postulated trial hypocenters and seismic recording stations is used to adjust the trial location iteratively until specified solution criteria are met. HYPOINVERSE allowed the use of crustal seismic-velocity models composed of flat-lying layers

with horizontal interfaces, in which the seismic velocities are specified in terms of depth-varying linear gradients. For such gradient models, including the one used at HVO for routine earthquake locations (Klein, 1981), fewer parameters are required to specify realistic depth-varying seismic-wavespeed distributions in the Earth, while maintaining the efficiency desired or required for routine hypocentral estimation. HYPOINVERSE also accounted for the elevation differences between stations by allowing for specification of adjustments, called station delays, to be applied to respective arrival times.

HYPOINVERSE also calculated earthquake magnitudes. The program included specification of seismograph calibrations for several seismometer and recording system types. Data analysts were able to pick maximum phase amplitudes on the Eclipse graphics terminal or to enter peak amplitudes, as measured from drum-paper records, into the HYPOINVERSE phase-arrival input files to determine amplitude-based earthquake magnitudes. In addition, analysts measured event coda durations on the Develocorder viewing screen as part of their daily scanning practice. They entered these durations into the HYPOINVERSE calculations to compute coda-duration magnitudes.

HVO's onsite computer with HYPOINVERSE afforded useful flexibility. For episodes of abnormal seismicity, the 40-s minimum cataloging threshold was typically relaxed, and the intention was to simply locate as many earthquakes as possible. On occasion, during volcanic microearthquake swarms, arrival-time readings from the Develocorder viewers were hand-entered into HYPOINVERSE runs to obtain computer-generated hypocentral information while the swarm was in progress. Of particular interest on these occasions would be estimates of earthquake location and focal depth that might reflect shallowing of seismicity before a possible eruption. Together with HYPOINVERSE, Klein also developed collections of computer utilities for graphical display of earthquakes and manipulation of earthquake catalogs (for example, Klein, 1983, 1989a).

Among the numerous reports that have drawn from the HVO seismicity catalogs produced from Eclipse data and HYPOINVERSE, perhaps none deserves mention more than the authoritative compilation by Klein and others (1987) that described earthquake distributions at Kīlauea in both space and time from 1960 through 1983. From the details observed in these patterns, Klein and coauthors systematically described individual earthquake swarms related to magmatic intrusions and eruptions, and articulated the relationships between seismicity and magma movement through Kīlauea's magma system. Koyanagi (1987) offered a similar compilation and discussion of Mauna Loa's magma system.

Summary plots of seismicity, presented in map and cross section views of the two volcanoes from these compilations, are shown in figures 9 and 10. These plots evoke a comparison with those of Eaton and Murata (1960) or Eaton (1962), but with the increasing numbers of earthquakes available in these later compilations, hypocentral distributions were used to infer greater details in the magma systems of the volcanoes. For example, Klein and others (1987)

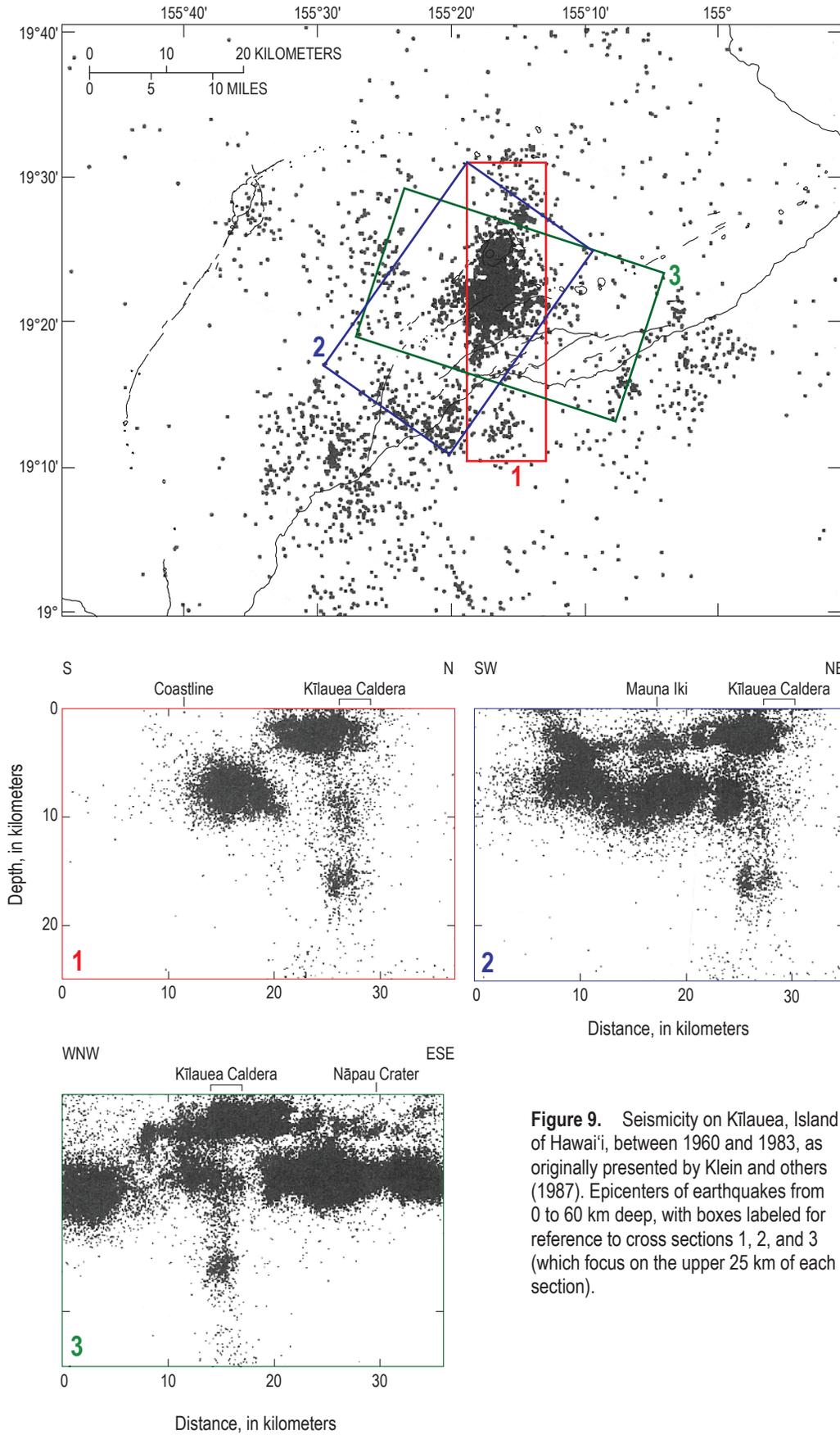


Figure 9. Seismicity on Kīlauea, Island of Hawai'i, between 1960 and 1983, as originally presented by Klein and others (1987). Epicenters of earthquakes from 0 to 60 km deep, with boxes labeled for reference to cross sections 1, 2, and 3 (which focus on the upper 25 km of each section).

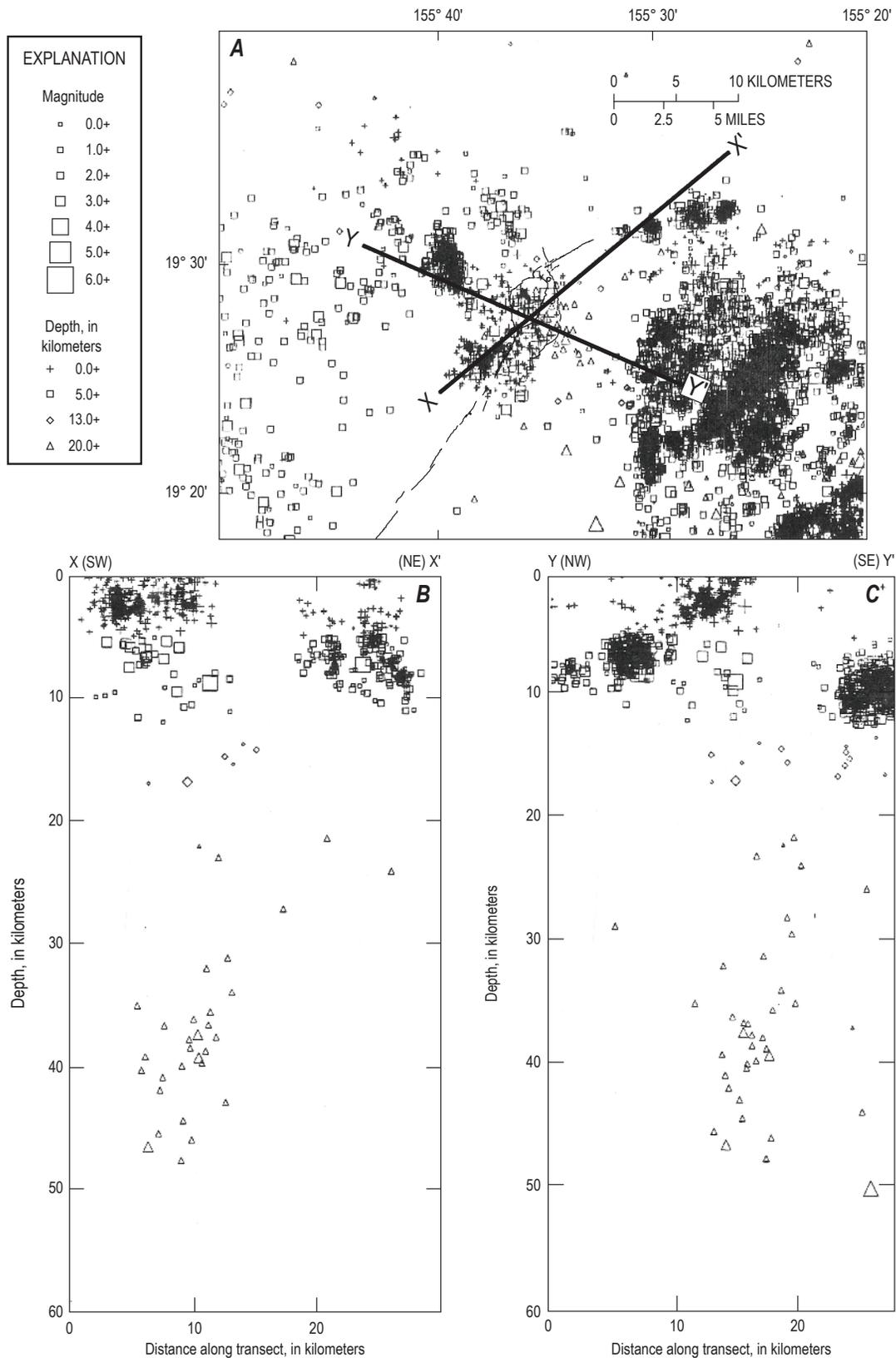


Figure 10. Seismicity beneath Mauna Loa, Island of Hawai'i, from January 1974 through April 1984, as originally presented by Koyanagi (1987). *A*, Earthquakes beneath Mauna Loa's summit and adjacent flanks, with epicentral symbols indicating focal depth, and symbol size indicating earthquake magnitude. *B*, Cross section of earthquake hypocenters, projected onto a vertical plane parallel to line X-X' in part *A*. *C*, Cross section of hypocenters projected onto a vertical plane parallel to line Y-Y' in part *A*. Hypocenters within 5 km of lines X-X' and Y-Y' are included in cross sections.

pointed to gaps in seismicity centered 5 km beneath Kīlauea as possible indicators of low rigidity that would be consistent with a magma chamber in the summit caldera region. They also identified seismicity beneath Mauna Loa that extends to depths of 50 km and may represent a magmatic root to that volcano. Koyanagi (1987) discussed this feature at greater lengths in his study of Mauna Loa's magma system and established that Mauna Loa and Kīlauea share similarities in seismicity patterns involving summit and rift-zone eruptive features. Seismic network coverage and Kīlauea's higher rates of intrusive and eruptive activity have allowed greater refinement of the concepts that he contended also apply to Mauna Loa.

Aki and Lee (1976) demonstrated the feasibility of using measured local-earthquake seismic-wave arrival times, along with cataloged hypocentral locations and origin times, to determine the distribution of seismic wavespeeds in three dimensions beneath a section of the USGS's Northern California Seismic Network. As their technique was embraced and adapted, the procedure, which became known as local earthquake tomography, has since been applied in various settings. Thurber (1984) was the first to apply local earthquake tomography to Kīlauea, using data from the HVO seismicity catalog consisting of P-wave-arrival times and the locations of 85 earthquakes recorded in and around Kīlauea's summit caldera region in 1980 and 1981. The results of P-wave tomographic modeling revealed a region of anomalously high V_p values interpreted as Kīlauea's summit magma complex, as well as high-velocity anomalies in the intrusive cores of Kīlauea's East and Southwest Rift Zones.

In addition to studies using the parametric hypocentral information compiled in the HVO seismicity catalogs, the Eclipse recording system preserved digital seismic waveforms, played back from the analog FM tape-recording system and reviewed to pick arrival times for building HYPOINVERSE catalogs. Got and others (1994) used cross-correlation techniques on the digital waveforms recorded on the Eclipse system between 1979 and 1983 in an early study of the fault geometry beneath Kīlauea's mobile south flank. Rubin and others (1998) conducted a similar study of microearthquakes associated with the magmatic dike intrusion leading to Kīlauea's currently ongoing East Rift Zone eruption, which began in 1983. Identifying earthquakes whose waveforms closely correlated with those of other earthquakes established multiplets, or families of earthquakes, defined by their highly correlating seismic waveforms, occurring in specific regions beneath Kīlauea's south flank (Got and others, 1994) and East Rift Zone (Rubin and others, 1998). By determining the arrival-time differences among earthquakes in a multiplet from waveform cross-correlations, they were able to locate earthquakes within the multiplets to levels of precision significantly beyond that of routinely produced HYPOINVERSE catalogs.

From their original selection of earthquakes in the HVO seismicity catalogs, Got and others (1994) defined earthquake multiplets as families of earthquakes in which each event has at least 90 percent coherency with at least 30

other events in the same family. These criteria resulted in an earthquake multiplet containing 252 events, whose hypocenters are shown in cross section in figure 11B. Got and others (1994) suggested that a significant fraction of Kīlauea's south-flank seismicity occurs within a relatively thin layer or fault at ~8 km below the Earth's surface. Although they analyzed seismicity associated with a rather small part of Kīlauea's south flank, they suggested that the details of fault geometries derived from precise relocations of earthquake multiplets influence Kīlauea's geodetically measured deformation and surface-displacement patterns.

Automated, Near-Real-Time, and Enhanced Seismic Data Processing at HVO, 1985–2009

Although the Eclipse/HYPOINVERSE system performed well in Hawai'i, attempts to use it in Menlo Park were less successful, most likely because of the larger number of seismographic stations operated by the USGS and its monitoring partners in Northern California. Through the late 1970s, Carl Johnson at Caltech designed and built a system for the seismic network in Southern California, for real-time digital data acquisition and automated, near-real-time event detection and processing on an online minicomputer. Interactive data analysis and postprocessing were carried out on a second, offline minicomputer (Johnson, 1979). Johnson joined the USGS and continued working in Pasadena to develop an improved seismic processing system, which evolved into the Caltech-USGS Seismic Processing (CUSP) system (Dollar, 1989; Lee and Stewart, 1989). He later served HVO from 1985–89.

As with Johnson's system at Caltech, CUSP received telemetered seismic data signals and converted them into a digital stream, using an analog-to-digital (A/D) converter. It also passed the digital data through a series of automated processing steps beyond A/D, leading to automatic hypocentral estimation on event "trigger" files if sufficient numbers of arrival-time picks could be assigned automatically, on an online or real-time computer system. Then the event triggers were passed to an offline analysis and postprocessing minicomputer for interactive review on graphics terminals. Readings were added from paper records, especially for determining earthquake magnitudes. The automation implemented in CUSP obviated the need to play back analog tapes in order to produce digital files for analysis and archiving, as well as providing seismic analysts with preliminary phase picks and hypocentral coordinates as they began their interactive data review. A custom database was integral to CUSP's event-processing and archiving environment.

The Northern California Seismic Network group in Menlo Park was optimistic with regard to how CUSP could help address its seismic processing needs and, in 1984, set up a test CUSP system. HVO was recommended to follow suit as a

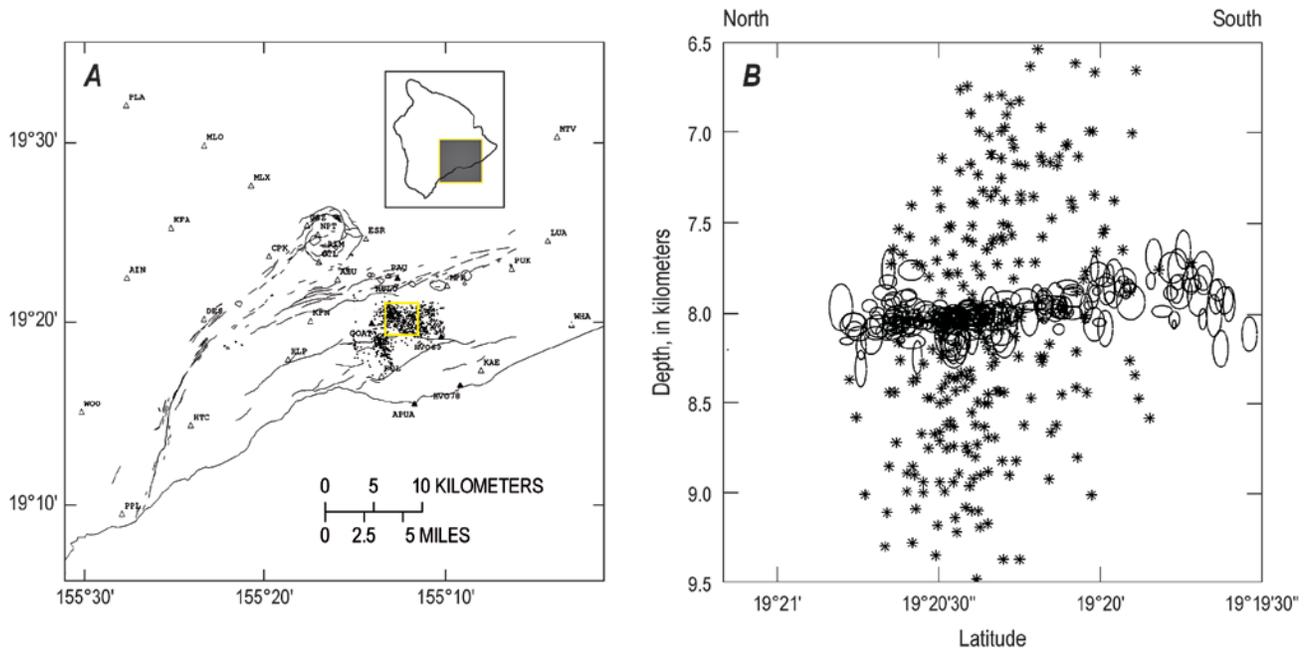


Figure 11. Earthquake relocations beneath Kilauea, Island of Hawai'i, modified from Got and others (1994). *A*, Epicenters of initial selection of earthquakes, $1 < M < 2.5$, with hypocenters of 5 to 10 km deep, with readings from more than 12 seismographic stations used in computer location, along with HVO stations and geologic and volcanic features. *B*, North-south cross section of hypocenters of largest multiplet of earthquakes consisting of more than 250 events within box plotted in part *A*. Stars, HVO catalog hypocenters; ellipses, relocated hypocenters, constrained such that centroids of HVO catalog and relocated hypocenters are identical. Sizes of ellipses are proportional to uncertainties in relative relocations.

means of modernizing its seismic data acquisition and analysis capabilities and procedures by using CUSP's automated utilities. In late 1985, CUSP systems were set up at HVO with two Digital Equipment Corp. VAX minicomputers and a graphic analysis terminal. At that point, the three largest USGS-supported regional seismographic networks—in Northern California (based at Menlo Park), Southern California (at Pasadena), and Hawai'i (at HVO)—had brought CUSP online. Adding CUSP's offline computer at HVO also expanded HVO's general, as well as seismic, computing capabilities.

Implementation and further improvement of CUSP proceeded somewhat independently among the various USGS CUSP sites. Specific local needs were addressed, and procedures were adapted to the local network setting. By 1992, CUSP development and support consolidated into a group based at the USGS Pasadena office. Among the principal advances achieved were the addition of continuous recording of seismic traces onto small-format digital tapes and the successful porting and implementation of CUSP utilities to take advantage of the availability of capable workstation computers configured in local-network clusters. Such a configuration greatly enhanced the passing of data among real-time acquisition and processing computers and analysis workstations. Also noteworthy was the creation in the mid-1990s of ISAIAH, or Information on Seismic Activity in a Hurry, a utility that would automatically issue earthquake notifications by email in near-real time (Wald and others, 1994).

With CUSP's automated earthquake data acquisition and processing, HVO was able to catalog greater numbers of earthquakes (see fig. 4), although scanning of Develocorder films continued for compiling daily and hourly counts of earthquakes. To maintain consistency with the reporting threshold of $M 1.5$ in earlier published seismicity catalogs, earthquakes whose durations read from the Develocorders exceeded 40 s were flagged, and their arrival times were extracted from the CUSP database. Hypocenters and magnitudes for these earthquakes were calculated with HYPOINVERSE, maintaining continuity with the HYPOINVERSE catalog that began when the Eclipse computer was installed in 1979. When the last HVO Develocorder failed irreparably in 1997, HVO data analysts built the lists of earthquakes for the published HVO HYPOINVERSE catalogs by using durations measured from drum-paper records.

Working in Menlo Park, Klein continued to support and adapt HYPOINVERSE through several updates (Klein, 1989b, 2002). Across updates of HYPOINVERSE, HVO reran older seismicity catalogs to maintain backward consistency through all HYPOINVERSE-computed locations and magnitudes. HVO also processed phase-arrival data dating back to 1959. Ultimately, HVO built an internally consistent, HYPOINVERSE-computed catalog of Hawaiian seismicity of nearly 150,000 earthquake hypocenters and magnitudes spanning 50 years, from 1959 to 2009.

The principal products derived from HVO's CUSP systems continued to be a seismicity catalog and an archive of seismic

waveforms associated with the cataloged events. Fulfilling HVO’s seismic monitoring and cataloging requirements, while adding the capability to closely track seismicity in near-real time, CUSP also afforded the ability to record and process significantly greater numbers of earthquakes in Hawai‘i. CUSP’s modular design and the introduction of computer workstations allowed tasks, including interactive review and timing of earthquakes, to be distributed among a group of seismic analysts and computer platforms. In turn, along with improved computing capabilities, this distribution of tasks motivated further implementation of extended seismic analysis techniques that, with repeated or more routine application, could be thought of as enhanced or more interpretative seismic monitoring products for HVO’s volcanic setting.

Seismic tomography, as pioneered by Aki and Lee (1976), is one of the more immediate extensions of a seismicity catalog,

especially if the seismic-wave-arrival times that are used in routine earthquake hypocentral estimation are carefully read and confirmed by seismic analysts. Okubo and others (1997) and Benz and others (2002) revisited Thurber’s initial tomographic P-wave imaging of Kīlauea’s summit caldera region, using early HVO CUSP data from 1986 through 1992. In their calculations, they included more than 110,000 P-wave-arrival times from more than 4,700 earthquakes and expanded the size of the tomographically imaged region to include the summit and southeastern flank of Mauna Loa (fig. 12; see Denlinger and Morgan, this volume, chap. 4).

Other tomographic imaging projects have followed, often complementing the arrival-time dataset assembled by HVO staff, with arrival times derived from temporary deployments or surveys targeting more specific imaging targets on and around the Island of Hawai‘i, such as Kīlauea’s summit caldera

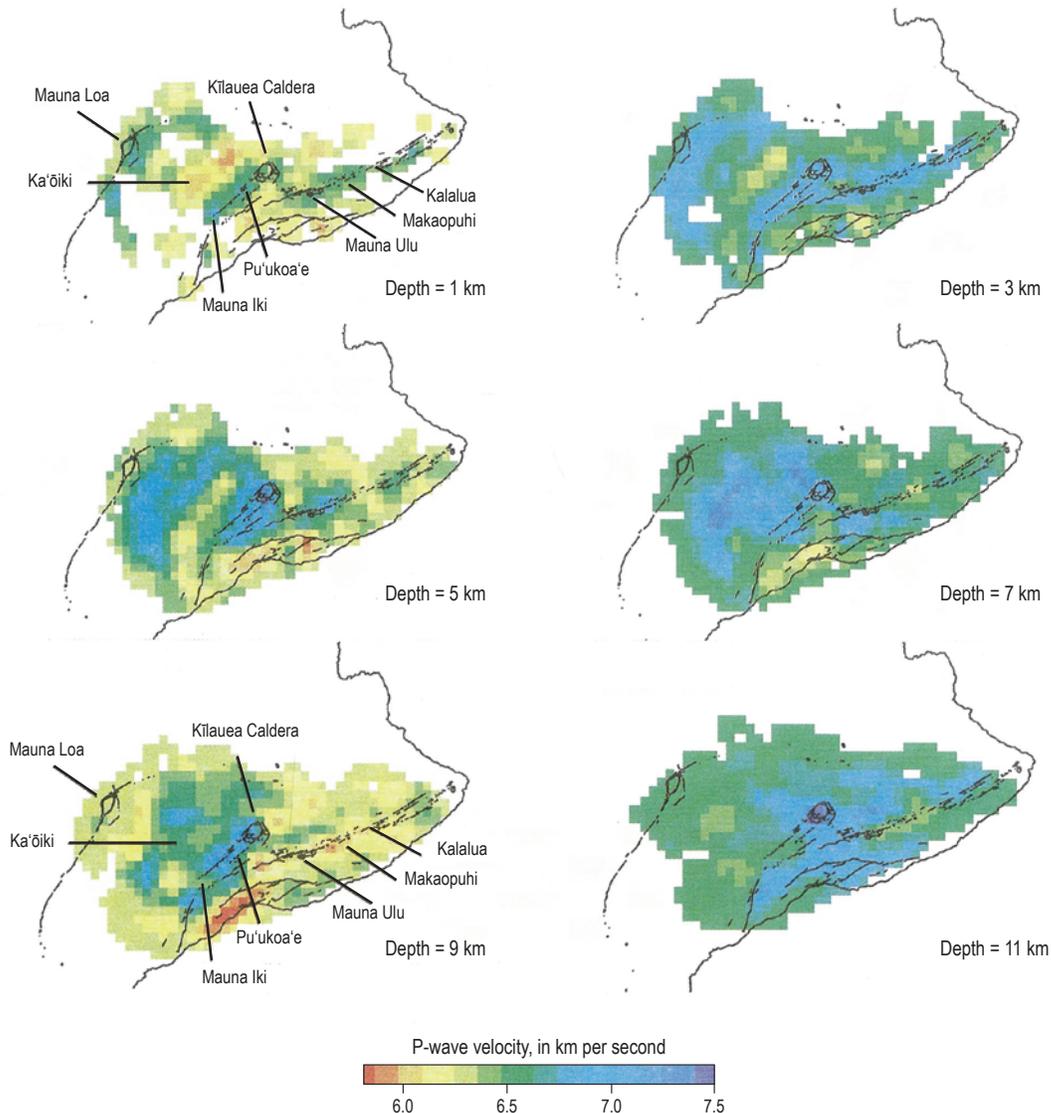


Figure 12. Selected slices from tomographic models of Benz and others (2002), showing volcanic craters and rift zones and seismic P-wave-velocity (V_p) distributions at different depths. Zones of high velocities are interpreted as olivine cumulates that resulted from repeated cycles of intrusion and eruption and that may be a driving force behind instability of Kīlauea’s south flank.

(Dawson and others, 1999), the offshore region adjacent to Kīlauea's south flank (Park and others, 2009), and Kīlauea's subaerial south flank (for example, Hansen and others, 2004; Syracuse and others, 2010).

The precise relocation of earthquake hypocenters by Got and others (1994) is another extension of the basic seismic network cataloging products. Following their example of relocating hypocenters beneath Kīlauea's south flank, precise relocation analyses that include the cross-correlation of seismic waveforms have been applied to other earthquake source zones and earthquake types, as identified in the HVO catalogs. Striking differences between cataloged and subsequently relocated hypocenters afforded very different views of seismicity distributions and earthquake processes. For example, Battaglia and others (2003) precisely relocated hypocenters of two families of LP earthquakes within Kīlauea's summit caldera and showed that one family of LP events lies directly beneath the east rim of Halema'uma'u Crater 500 m below the surface, whereas another lies 5 km beneath the east rim of Kīlauea caldera northeast of Keanakāko'i Crater (fig. 13). Instead of a diffuse pattern of hypocenters suggestive of a volume of LP seismic sources, as indicated in the traditional HVO seismicity catalogs, the relocated seismicity suggests that the systems of cracks comprising the crater rims in these areas may extend as deep as 5 km and that LP sources do not fully trace magma pathways beneath Kīlauea's summit caldera. Instead, combinations of stress, pressure, temperature, and crack

geometry in these places are favorable to generating LP seismic-energy release (Battaglia and others, 2003).

A similar waveform correlation-based treatment of an unusual sequence of deep LP seismicity beneath Mauna Loa from 2002 and 2004 established that the distribution of cataloged hypocentral solutions, forming a nearly vertical source region >20 km in vertical extent, could be quite misleading (Okubo and Wolfe, 2008). The relocated hypocenters, again using waveform cross-correlations, reduced the spread (as routinely located) of these LP hypocenters to two clusters, both centered beneath Mauna Loa's summit caldera at depths of 36 and 45 km (fig. 14). Rather than tracing a magma pathway from the mantle into Mauna Loa, the LP hypocenters reflect regions where conditions are favorable to LP seismic energy release.

Systematic relocation of the entire HVO CUSP catalog is currently underway, using the waveform cross-correlation and cluster analysis techniques described by Matoza and others (2013). Rather than targeting specific earthquake source regions for relocation, Matoza and coworkers have thus far systematically relocated 101,390 of the 130,902 events spanning the 17-year interval between 1992 and 2009. The sharpening of details visible in the relocated earthquake distributions along faults, fault streaks, and magmatic features will provide important constraints on future studies of fault geometry and tectonic and volcanic processes. Research continues to include CUSP data from 1986 through 1991 and to improve upon the systematic relocation of volcanic LP events.

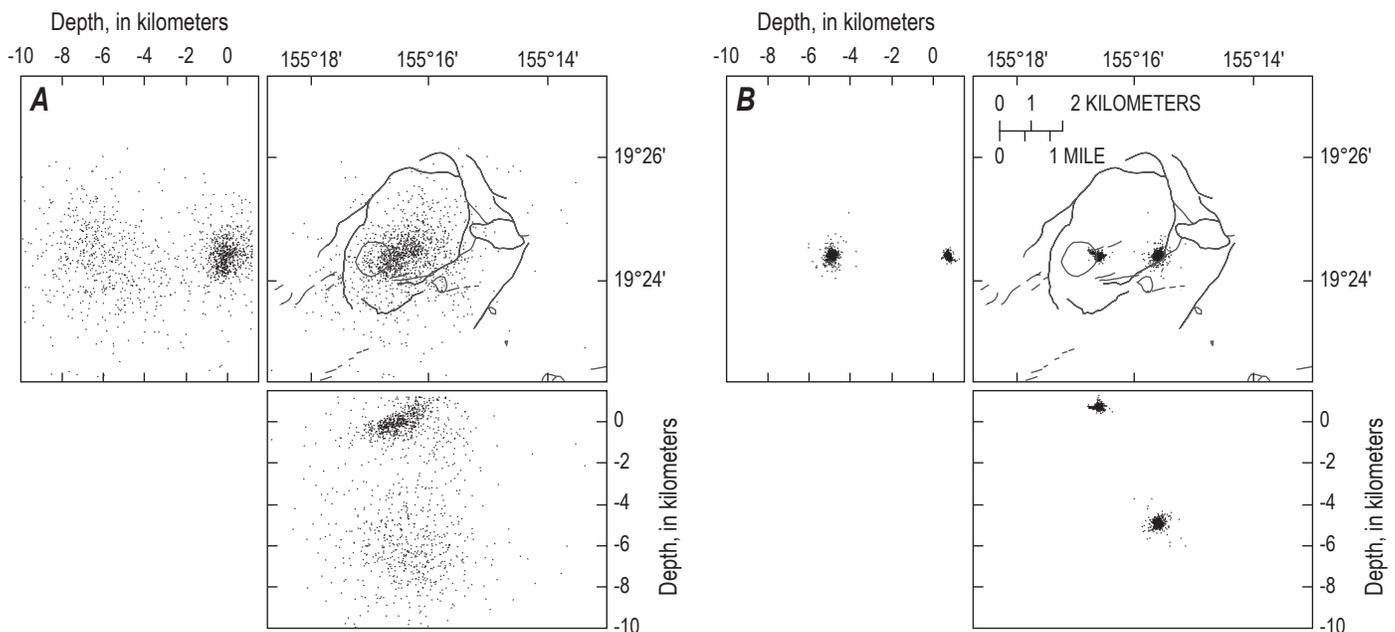


Figure 13. Precise relocations of 1,322 long-period earthquakes that occurred during January 1997–December 1999 beneath Kīlauea, Island of Hawai'i, modified from Battaglia and others (2003). A, Original Hawaiian Volcano Observatory catalog earthquake locations in map view (upper right), north-south cross section (left), and east-west cross section (bottom). B, Relocated hypocenters of earthquakes in map view (upper right), north-south cross section (left), and east-west cross section (bottom).

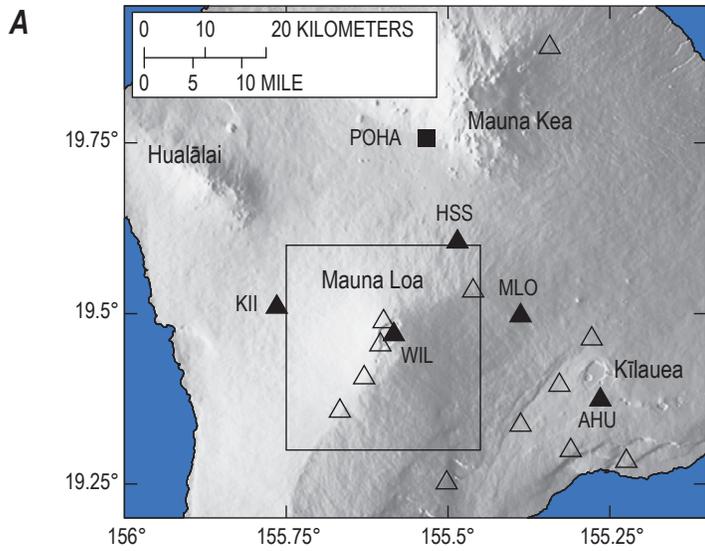
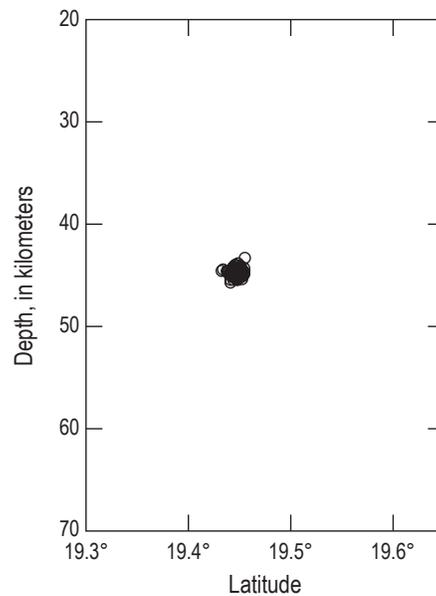
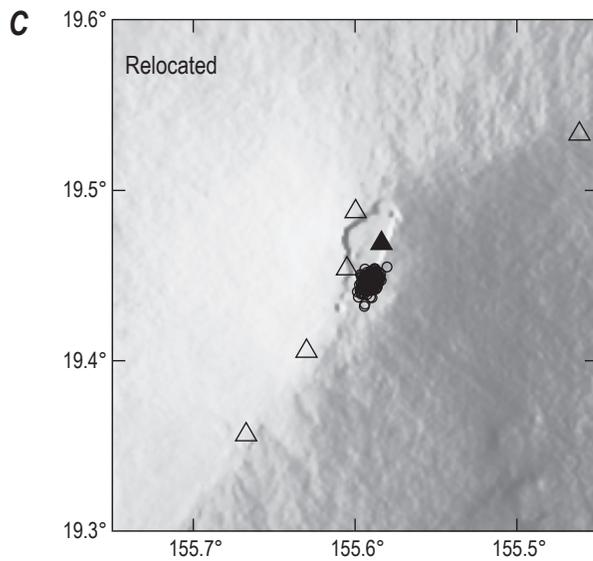
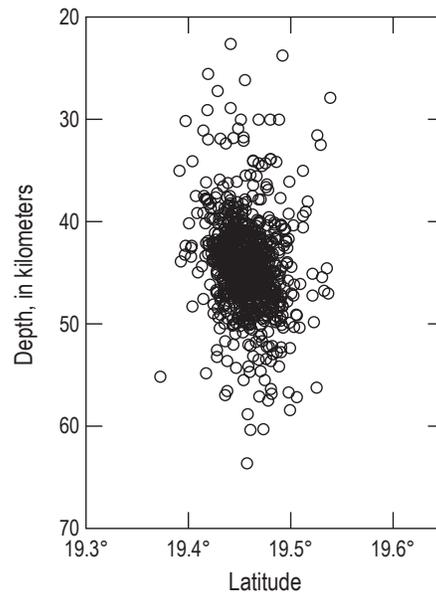
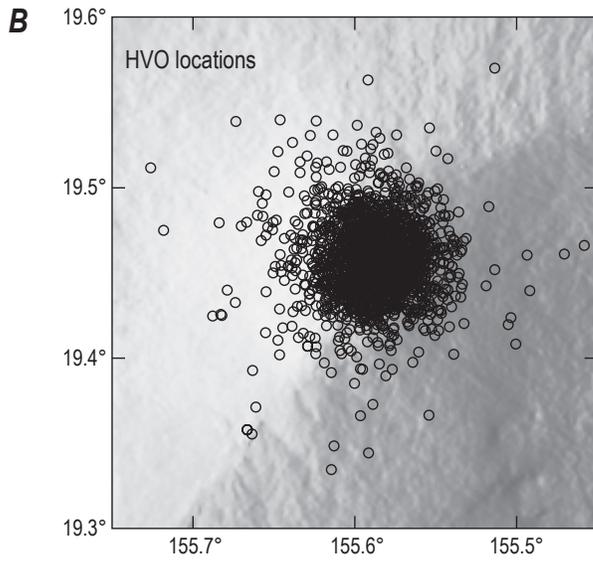


Figure 14. Island of Hawai'i, showing precise relocations of long-period earthquakes beneath Mauna Loa, modified from Okubo and Wolfe (2008). *A*, Seismic network used for relocations. Open triangles, vertical-component stations; solid triangles, three-component stations (with station names); square, Global Seismographic Network station. Box shows area covered in parts *B* and *C*. *B*, Hawaiian Volcano Observatory catalog of earthquake locations below 20-km depth between August 2004 and December 2005 in map view (left) and depth section (right). *C*, Relocated hypocenters of earthquakes shown in part *B* in map view (left) and depth section (right).



Beyond Microearthquake Monitoring

Broadband Monitoring

The basic CUSP requirement was to compile regional microearthquake catalogs from seismic networks. When CUSP was conceived and built, USGS seismic network operations were constructed around the USGS high-gain, short-period, analog FM, voice-grade telemetry systems designed, built, and improved in Menlo Park. CUSP was therefore written to drive the A/D conversion of seismic data inputs and had to be written to work with specific A/D units. What was originally a design specification in terms of the seismic data source therefore became, in a sense, a limitation of CUSP as digital capabilities became increasingly more accessible to seismic data telemetry. CUSP was also designed and principally operated in California and Hawai'i, where relatively large USGS seismic networks were recording high levels of seismic activity. These aspects also limited CUSP, because its design around high-bandwidth A/D conversion, using moderately capable mini-computers and workstations, made it difficult to adapt CUSP to seismic monitoring efforts that were smaller in operational scope, staffing, and (or) support.

Microearthquake cataloging remains an aspect of earthquake and volcano monitoring of the utmost importance. Simultaneously, the scope of regional seismic monitoring needs to be extended to lower frequencies in the seismic spectrum in order to provide information about seismic source physics by using broadband seismic instrumentation. Computing technologies, including the Internet and the Global Positioning System (GPS), have developed and matured, allowing digital seismic telemetry, recording, and data processing to expand and diversify.

As personal computers (PCs) became increasingly more common, seismologists began to explore PC-based computer systems for acquiring and processing seismic data, notably Willie Lee of the USGS in Menlo Park, who developed what has become the IASPEI Seismological Software Library (Lee, 1989). The capability and value of IASPEI PC systems were clearly demonstrated by their use during the Mount Pinatubo volcanic crisis in 1991 (Harlow and others, 1996). The USGS network group in Northern California was quite interested in adding broadband monitoring to its operational scope. Lee and colleagues developed a PC software module to match a digital seismic telemetry (DST) field unit designed and built by USGS engineer Gray Jensen.

HVO, Lee, and USGS Menlo Park colleague Bernard Chouet agreed to conduct a broadband seismic monitoring field test at Kīlauea in late 1994. Chouet provided the seismometers, borrowing several broadband instruments from colleagues to match 10 DST units built by Jensen. Lee brought IASPEI PC systems to HVO to record DST seismic data. The DST effort evolved from field test to a long-standing HVO

operational research collaboration with Chouet's project in Menlo Park. The locations of the DST seismographic stations in the Kīlauea summit caldera region are shown in figure 15.

Establishing the broadband seismometer subnet within Kīlauea Caldera resulted in important improvements to HVO's ability to monitor seismicity in the summit region. Adding 10 more seismographic stations within this region necessarily meant smaller interstation distances, with commensurate improvement in resolving finer details in hypocentral distributions and seismic velocity heterogeneity beneath the caldera. The Kīlauea broadband seismometer subnet served as the anchor for a temporary deployment of 116 seismometers at Kīlauea in 1996 (McNutt and others, 1997). Dawson and others (1999) were able to update the tomographically derived seismic velocity models of Kīlauea's summit caldera region by using nearly 8,000 P- and S-wave arrival-time readings from 206 earthquakes. With the additional stations available for their calculations, Dawson and others (1999) cited a tomographic model resolution of 500 m, in comparison with the 2- to 3-km resolution available to Thurber (1984) and Okubo and others (1997). The resulting seismic velocity models for both V_p and V_p/V_s (fig. 16) suggested distinct but connected magma reservoirs beneath the southern part of the summit caldera and extending into Kīlauea's upper East Rift Zone.

Broadband recording at Kīlauea revealed dynamic excitation of the volcano that was not previously known because it is composed of seismic wave oscillation frequencies of 0.05 Hz (20 s) or lower (Dawson and others, 1998). This frequency range, which is considered to be very-long-period (VLP), lies considerably below the traditional 0.5 to 5 Hz LP band of volcanic and seismic processes and is poorly recorded

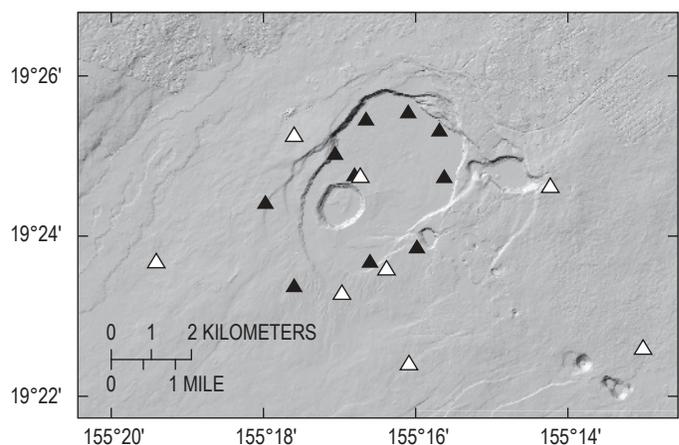


Figure 15. Kīlauea Caldera, Island of Hawai'i, showing locations of Hawaiian Volcano Observatory (HVO) seismographic stations in 1996. White triangles, high-magnification, short-period stations with data recorded by HVO's CUSP system; solid black triangles, stations equipped with U.S. Geological Survey Digital Seismic Telemetry units that were eventually upgraded to broadband seismic sensors.

on short-period microearthquake instruments (which made up the bulk of the Kīlauea seismic network in the 1990s). Taking advantage of the full waveform content of broadband recordings, Chouet and colleagues have cataloged and modeled, using the moment tensor seismic source representation, VLP sources at Kīlauea (for example, Ohminato and others, 1998; Dawson and others, 2010), and they continue to develop seismic source models to explain the geometry and physics of VLP excitation. Most recently, Chouet and Dawson (2011) have articulated the geometry of the shallow conduit system feeding the current eruption at Halema'uma'u Crater. They modeled seismic waveforms of tremor bursts related to degassing at Halema'uma'u by using the seismic velocity model of Dawson and others (1999), and suggested that VLP seismic sources beneath the east rim of Halema'uma'u Crater are associated with a complex of intersecting dikes within Kīlauea's shallow magmatic plumbing system (Chouet and Dawson, 2011).

Earthworm and Tsunami Hazard Mitigation

In late 1993, the USGS chose to support the creation of a new seismic processing system to address many shared concerns identified by seismic network operators both within and external to (but supported by) the USGS. USGS software developers Alex Bittenbinder and Barbara Bogaert consulted with, and ended up collaborating with, Carl Johnson (who had moved from the USGS to the University of Hawai'i, Hilo) to design and eventually build and implement the new system. Key features of this new system included modularity and scalability to meet the needs of both large and small seismic networks, as well as the ability to support data exchange among a diversity of digital data sources, ranging from A/D converters to seismic instrumentation or data streams from cooperating network partners. Design goals

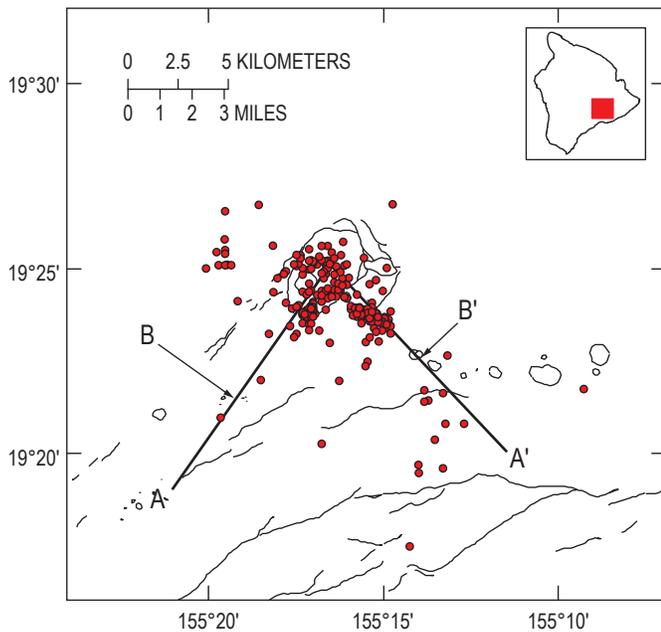
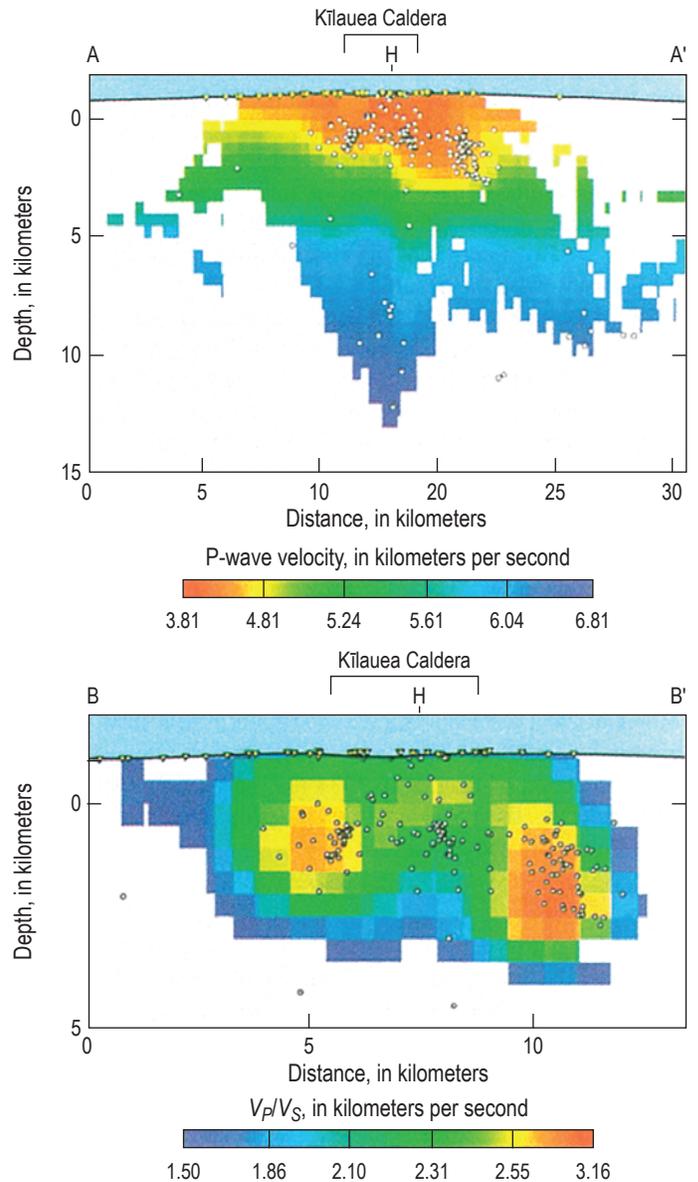


Figure 16. Seismic velocity structure of Kīlauea Caldera region, Island of Hawai'i, showing cross sections of V_p and V_p/V_s from Dawson and others (1999). Reference map at top left shows locations of earthquakes used in tomographic imaging calculations, as well as locations of cross sections A–A' and B–B' that are hinged at a point adjacent to Halema'uma'u Crater within the summit caldera. Anomalously low V_p and high V_p/V_s features within the summit caldera and extending into Kīlauea's Southwest and East Rift Zones are interpreted to indicate locations of magma bodies.



were also sensitive to allowing network operators to configure and adapt their systems as needed, with sustainability even for seismic networks where staffing support is limited. The project was named Earthworm (Johnson and others, 1995).

Earthworm was designed as an object-oriented message-broadcasting system with network utilities built into program modules. Interacting modules can be set up on separate computers to communicate by using a local area network infrastructure, or on the same computer to communicate by way of shared memory buffers. Other important decisions were to strive toward platform neutrality by initially programming for both Sun and Intel computer architectures, to help achieve the goal of scalability according to an individual network's needs and resources. The Earthworm system software, except for proprietary code specific to particular hardware (like software to control an A/D converter), was freely and openly available. Earthworm has been embraced by numerous, typically smaller, seismic networks across the United States and around the world, allowing for the implementation of a community-support model for offering and obtaining Earthworm technical assistance.

In 1999, upon a recommendation from the National Tsunami Hazard Mitigation Program (NTHMP), HVO and the National Oceanic and Atmospheric Administration (NOAA) Pacific Tsunami Warning Center (PTWC) were given the opportunity to improve notification and warning capabilities in connection with tsunamis generated by large earthquakes in Hawai'i. Installing Earthworm systems at both centers allowed HVO and PTWC to replace an analog FM radio link for seismic data with Earthworm data imports and exports over the Internet, enabling greater sharing of data between the two centers. This implementation allowed HVO to collect all of its incoming analog seismic data by using an Earthworm A/D converter. The NTHMP upgrades also resulted in the installation of three combined broadband and low gain, or strong-motion, seismographic stations outside Kīlauea caldera. Available Internet bandwidth limited the initial Earthworm exchanges to ~40 data channels, which were nonetheless a considerable increase over the 8 channels sent by way of the earlier FM link. Because no interactive utility had been written at that time for Earthworm to efficiently review earthquakes, HVO continued to use its CUSP systems for seismic monitoring and cataloging on the Island of Hawai'i.

Advanced National Seismic System, M6+ Earthquakes in 2006

The timing of NTHMP upgrades coincided with that of discussions concerned with the seismic monitoring infrastructure of the United States. In 1997 the U.S. Congress enacted Public Law 105–47, which required that the USGS conduct an assessment of seismic monitoring across the United States, with particular focus on improving and updating monitoring infrastructure and expanding monitoring capabilities to include

recording strong ground motions, especially in urban areas. To comply with Public Law 105–47, in 1999 the USGS released Circular 1188, "Requirement for an Advanced National Seismic System: An Assessment of Seismic Monitoring in the United States" (U.S. Geological Survey, 1999). In 2000, Congress authorized full implementation of the Advanced National Seismic System (ANSS), as framed in USGS Circular 1188, over a 5-year period and required an implementation plan.

The first ANSS operational efforts focused on strong-motion monitoring in urban areas exposed to high seismic risk. In addition to recording data on strong ground shaking in urban areas caused by large local earthquakes, ANSS goals and performance were also articulated in terms of the generation of data and information products derived from recorded ground motion. One of the most important ANSS-derived data products is ShakeMap, which predicts the ground shaking caused by an earthquake (Wald and others, 1999a). Although the principal data for ShakeMap came from seismographic records, ShakeMap has since been enhanced to also use reports of earthquake effects and intensities, as compiled on USGS Community Internet Intensity Maps (Wald and others, 1999b), in automatically triggered calculation of ground-shaking distribution.

Instruments operated by the USGS National Strong Motion Project (NSMP, previously the National Strong Motion Program) were critical to the creation of ShakeMap. The NSMP operates strong-motion accelerometers in seismically hazardous regions, including Hawai'i, to record large earthquakes without exceeding the instrumental limits, in order to document the effects of large earthquakes on structures and the built environment. In 1999, NSMP and HVO agreed to upgrade 12 existing NSMP sites on the Island of Hawai'i with digitally recording accelerographs. In addition, these sites were to be set up to automatically connect and to upload their data by modem to NSMP servers in Menlo Park, after earthquakes large enough to satisfy their triggering algorithm. Neither HVO's CUSP nor its Earthworm systems were able to acquire and process data from NSMP instruments.

On October 15, 2006, a pair of damaging, M_6+ earthquakes struck the Island of Hawai'i. The first event, $M_6.7$, was centered ~40 km beneath Kīholo Bay on the northwest coast of the island. Just 7 minutes later, an $M_6.0$ earthquake occurred at a depth of ~20 km, centered north of the earlier earthquake, ~20 km offshore from Māhukona. In 2001, the USGS had implemented its Community Internet Intensity Map, or "Did You Feel It?" Web utility (Wald and others, 1999b), for earthquakes in Hawai'i. This utility allows reports of earthquake effects to be contributed by the general public to USGS servers. The reports are compiled and posted as map displays that show distributed earthquake effects. Along with data from NSMP digital instruments in Hawai'i, the "Did You Feel It?" reports (fig. 17A) were used in creating ShakeMaps of these two earthquakes (fig. 17B) that were posted the following day. The ShakeMap utility has since been configured to automatically generate ShakeMap products after earthquakes of $M_{\geq 3.5}$ in Hawai'i.

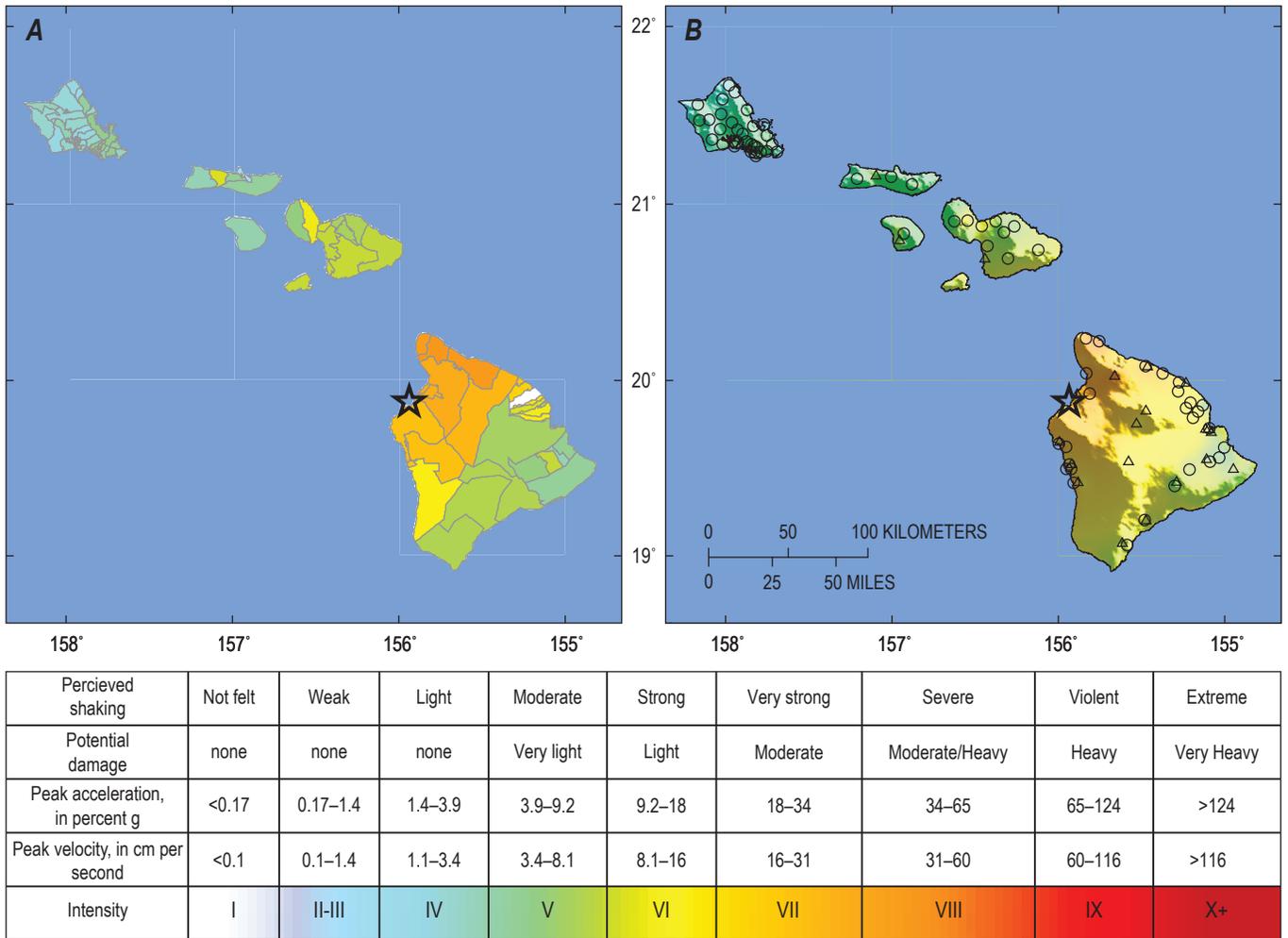


Figure 17. U.S. Geological Survey Community Internet Intensity Map (A), also referred to as “Did You Feel It?”, and ShakeMap (B) computed after the $M_{6.7}$ Kīholo Bay earthquake of October 15, 2006.

The 2006 earthquakes were large enough to saturate the recordings of HVO’s entire microearthquake monitoring system. The NSMP strong-motion instruments, including those installed with telemetry as part of the NTHMP upgrades, as well as those storing their data only onsite, recorded these earthquakes without clipping and provided an unprecedented collection of records for a damaging Hawaiian earthquake. Yamada and others (2010) used the available strong-motion records, along with records of aftershocks that defined a northwest-trending inferred rupture plane, in a study of the M_w 6.7 main shock. Yamada and others determined that the rupture propagated northwestward at >3 km/s, and inferred that aftershocks clustered about asperities, or regions on the rupture plane that sustained relatively large fault slip (fig. 18). This sequence was the first opportunity to study the rupture process of a damaging earthquake in Hawai‘i in such detail, as afforded by the number of onscale strong-motion records recovered after the main shock.

The 2006 earthquakes were the largest to strike Hawai‘i since the June 25, 1989, $M_{6.1}$ earthquake near Kalapana, along the southeast coast of the Island of Hawai‘i, and thus

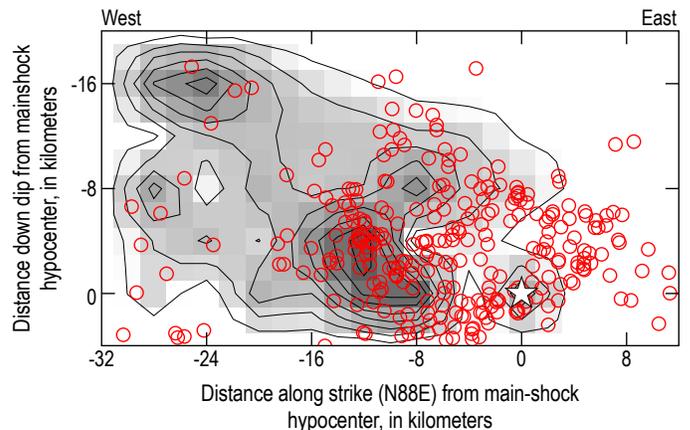


Figure 18. Faulting model of the $M_{6.7}$ Kīholo Bay earthquake of October 15, 2006, as inferred by Yamada and others (2010), showing contours (at 0.1-m intervals) of fault slip projected onto a south-dipping, east-trending fault plane defined by aftershock locations (red circles). Aftershocks are clustered on edges of asperities, or regions of large fault slip.

provided an opportunity to assess the ability of seismic monitoring in Hawai‘i to respond to large earthquakes, using modern instrumentation and methods. With respect to their principal monitoring missions and requirements, no failures occurred among HVO, NSMP, and PTWC with regard to their performances in response to these earthquakes. Simultaneously, it was recognized that there was room for a great deal of improvement in terms of rapid delivery of reliable, consistent, and robust earthquake information (Chock, 2006; William Leith, written commun., 2006). The delays may have been exacerbated by the shutdown of Internet services resulting from power outages across the entire state, which compromised electronic exchange of data and information among HVO, PTWC, and the USGS National Earthquake Information Center (NEIC) in Golden, Colo., and resulted in difficulties in coordinating earthquake reporting.

One recommendation included in the USGS assessment in the aftermath of the 2006 earthquakes was to install, at HVO, seismic data-processing software implemented by the California Integrated Seismic Network (CISN) by the USGS offices in both Menlo Park and Pasadena, along with their major university operating partners at Caltech and the University of California, Berkeley. This installation would afford HVO significantly upgraded data acquisition and processing capabilities relative to its legacy CUSP systems. The CISN software was designed to complement Earthworm data acquisition systems collecting digital seismic data from diverse instruments. Data from contemporary digital field dataloggers, used in conjunction with broadband and low-gain or strong-motion seismic sensors, could be seamlessly merged into HVO data-processing streams. In other words, strong-motion, broadband, short period, and other seismic data could be analyzed concurrently within the CISN processing environment to determine earthquake locations and magnitudes. In addition, data could be easily shared among HVO, PTWC, NSMP, and NEIC to not only meet their respective requirements but also to afford earthquake-reporting capabilities consistent with expectations and requirements of the ANSS.

The installation of California Integrated Seismic Network processing software in Hawai‘i, which was the first attempt to migrate the software from its established seismic processing environments in California, represented a test of how the CISN software could best be ported to other seismic networks. Since its initial installation at HVO in 2008, the software has been renamed the “ANSS Quake Management Software” (AQMS) and installed at USGS-supported regional seismic-network processing centers in Washington, Utah, Tennessee, New York, and Alaska.

Into HVO’s Second Century of Seismic Monitoring: 2009 and Beyond

In April 2009, HVO decommissioned its long-running CUSP systems and transferred routine seismic-data-processing

operations to the AQMS system. In addition to the DST seismic network of broadband sensors that continues in operation in Kīlauea’s summit caldera (fig. 15), the locations of seismographic stations operating on the Island of Hawai‘i and monitored by HVO as of 2009 are shown in figure 19. With support from the NTHMP, data from PTWC stations on the Island of Hawai‘i were also added into HVO’s AQMS streams, along with data from the Incorporated Research Institutions for Seismology (IRIS) Global Seismic Network (GSN) stations operated at Pōhakuloa Training Area (on the south flank of Mauna Kea) and at Kīpapa, O‘ahu (blue squares, fig. 19). With facilitated acquisition of data from diverse digital sources using AQMS, HVO is now also collecting strong-motion seismic data from USGS NSMP stations and USGS NetQuakes recorders (installed in the homes of private citizens and connected to the Internet), which automatically transmit event triggers to HVO through data servers in Menlo Park.

Also in 2009, HVO and the USGS in general were given unprecedented opportunities for network modernization with the passage of the American Reinvestment and Recovery Act. At HVO specifically, significant funds went to an extensive overhaul of HVO’s seismic field network, including upgrades to seismic sensors and the telemetry needed to transmit data from remote station sites to the seismic-data-processing center at HVO (Kauahikaua and Poland, 2012). As of 2013, HVO’s seismic telemetry backbone is entirely digital, affording sufficient bandwidth and dynamic range to achieve continuous broadband seismic monitoring coverage of the entire Island of Hawai‘i, as well as the ability to accommodate a greater diversity of sensors and allow all earthquakes of interest, ranging in magnitude from <1 to ≥ 8 , to be recorded onscale in real time. Establishing such capability extends the possible range of seismic source characterization of earthquakes in Hawai‘i to include moment tensor characterizations and others studies of earthquake rupture processes like that demonstrated by Yamada and others (2010). Although study (to the level of detail now accessible) of the rupture processes of Hawai‘i’s largest historical earthquakes—in 1868 (predating instrumental recording in Hawai‘i) and in 1975 (when local recording and analysis were focused on microearthquake locations and patterns)—is impossible, we can begin to explore and articulate interactions between future large earthquakes (such as those beneath volcanic flanks) and the magmatic storage and transport systems of active volcanoes.

A project of considerable interest is analysis of ambient seismic noise to detect changes in seismic wavespeed within Kīlauea (Ballmer and others, 2013), following the approach of Brenguier and others (2008) and Duputel and others (2009) at Piton de la Fournaise Volcano, La Réunion. At La Réunion, magmatic intrusions were accompanied by small but measurable decreases in seismic wavespeed within the volcanic edifice, eruptions were associated with increases in wavespeed, and a summit caldera collapse was marked by a large decrease in wavespeed. Ambient noise monitoring offers great promise for tracking changes in seismic wavespeed more reliably and consistently over time, because the measurements

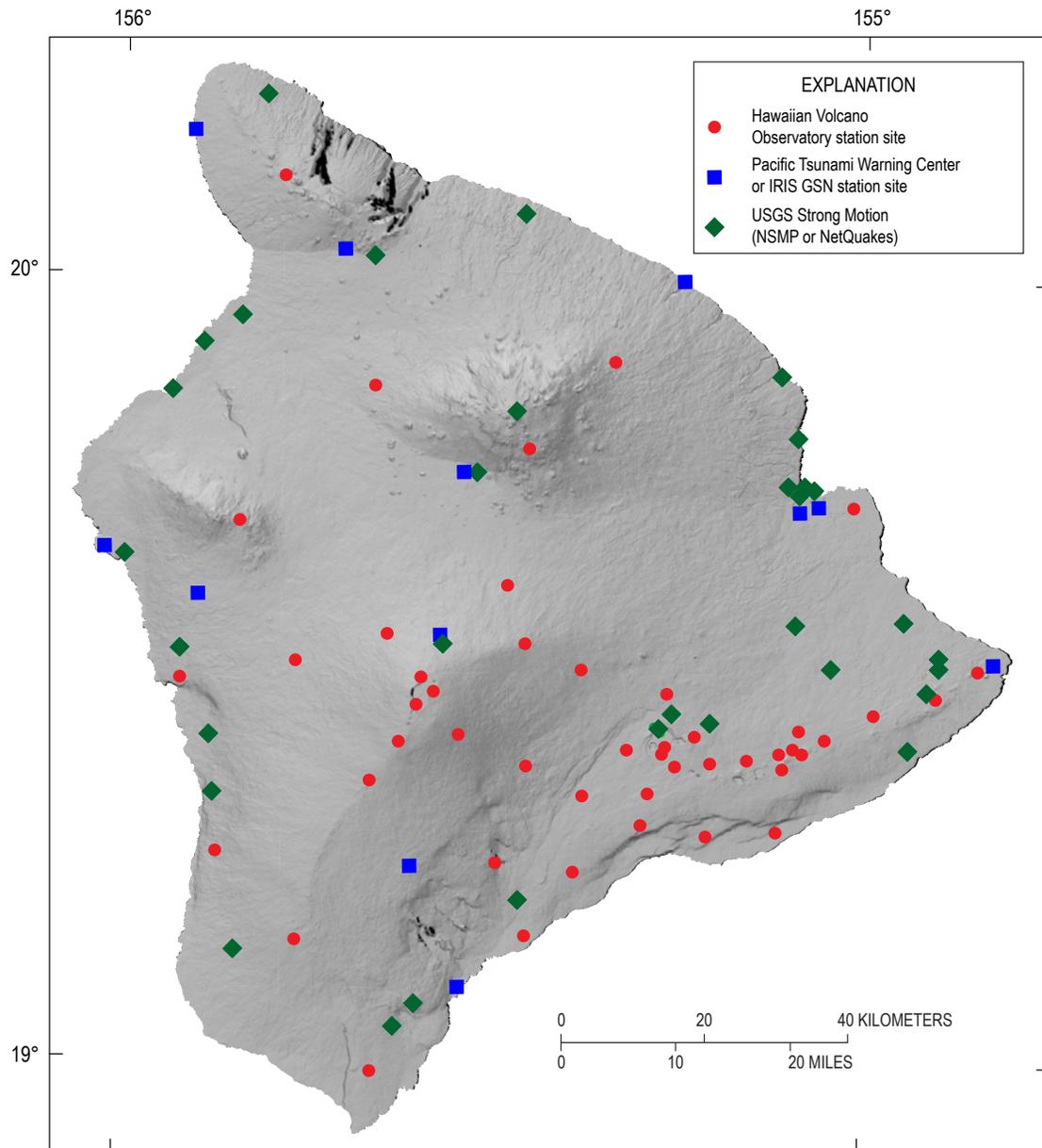


Figure 19. Map of the Island of Hawai'i, showing locations of seismographic stations as of 2009.

do not depend on earthquakes, which do not occur at steady rates, but rather on background microseismic noise—for example, noise caused by ocean waves on the island's shores. Ballmer and others (2013) have implemented ambient-noise analyses for HVO data and, in the process of looking for changes in seismic wavespeed, have succeeded in identifying the contribution to the ambient seismic noise wavefield on the Island of Hawai'i resulting from Kīlauea's continuing eruptions at the summit and East Rift Zone.

HVO, throughout its first century of seismic monitoring, has compiled a comprehensive catalog of earthquakes in Hawai'i and an extensive collection of records of the range of seismic events associated with active volcanism and tectonism. Implementation of improved monitoring and

analysis technologies has allowed monitoring products to expand beyond simply counts and qualitative descriptions of seismic events, as seen on the earliest drum-paper or film seismograms, to maps of earthquake locations and estimated distributions of strong ground shaking, earthquake magnitudes and focal mechanisms, and earthquake notifications, many of which are now produced and distributed automatically in near-real time.

Numerous investigators have drawn from HVO's digital collections of earthquake hypocenters and seismic waveforms to apply and develop quantitative analysis and modeling techniques and to extend geophysical and seismologic insights. Imaging of seismic-source distributions and three-dimensional seismic wavespeed distributions is improving, indicating

plausible positions of magma bodies and pathways. Moreover, by using three-dimensional seismic models of the volcanoes with advanced seismic source modeling tools, features of the magma transport system that feeds intrusions and eruptions can now be seismologically mapped.

A great deal of interest in, and a need for, increasing the content of automatically generated, near-real-time earthquake reporting products, including more dynamic updating of seismicity catalogs, already exists. Thus, it is not unreasonable to expect that greater emphasis will be placed on implementing such products for volcano monitoring and reporting purposes. Earthquake cataloging will continue to be an important enterprise, because future research will also depend on the availability of reliably reviewed seismicity catalogs. As analysis tools and techniques—both mentioned here as well as awaiting implementation and demonstration—are more routinely applied to data from HVO's modernized seismic systems, we can reasonably expect that routine reporting products from seismic networks in volcanically active regions will extend well beyond hypocentral location and magnitude to more completely describe volcanic and related seismicity.

Acknowledgments

From its very beginnings at HVO, like the observatory itself, seismic monitoring has been possible only through the dedicated and sustained efforts—both at HVO and at USGS offices in Menlo Park and Pasadena, California—of the many individuals committed to its continued success. We have named several of them as we documented HVO's seismic-network evolution through its first 100 years. Many important contributions over that period were not such as would lead to authorship on the reports and publications chosen here to mark evolutionary network growth. We would now like to acknowledge those who contributed from critical staff positions at HVO during its transitions through computer-based seismic network operations. Their efforts represent the groundwork for HVO's seismic network operation eventually becoming a conspicuous regional component of the USGS' Advanced National Seismic System. In approximately chronological order of joining HVO's staff, they are as follows: George Kojima, Kenneth Honma, Erwin MacPherson, Irene Tengan, Alex Bittenbinder, Thomas English, Robert Cessaro, Bruce Furukawa, Wilfred Tanigawa, Alvin Tomori, Gary Honzaki, Pauline Fukunaga, Renee Ellorda, Jon Tokuuke, Carol Bryan, Laura Kong, Alice Gripp, Steven Fuke, Stuart Koyanagi, Jeff Uribe, and David Wilson. In recognition of HVO's long-sustained operation of the USGS CUSP systems, we acknowledge vital contributions and support from Robert Dollar, Douglas Given, and Allan Walter of the USGS Pasadena, Calif., office. Finally, we thank Fred Klein, Wes Thelen (since 2011, HVO's seismic network manager, who can begin to write the next chapter of seismic network evolution), and Michael Poland for their reviews of the manuscript.

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